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A HYBRID APPROACH TO TACTICAL VEHICLES

by

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September 2011

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Combat operations are suffering from unnecessarily high fuel demand which degrades capability, exposes support operations to greater risk than necessary, and increases operations and support costs. This thesis describes the current suite of hybrid drivetrain technologies, evaluates their effectiveness in a tactical environment, and suggests an architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements. This thesis includes a comprehensive analysis of nine power sources and three general hybrid architectures against ten performance attributes using multiple criterion decision theory with considerations for selection criteria dependencies and vehicle duty cycles. The rating of selection criteria is not always a direct comparison of component performance parameters. In some cases, capabilities are dependent on the general hybrid architecture and on the form of energy storage in others. In a fully burden cost of fuel context, the capability of hybrid drivetrains to improve fuel economy of vehicles by up to 20% translates to $0.39-$83.54 billion in annual savings across the Army's tactical wheeled vehicle fleet depending on the fuel delivery method. The recommended hybrid drivetrain architecture is a series hybrid with a diesel engine primary power source, flywheel secondary power source, and permanent magnet traction motors.

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A HYBRID APPROACH TO TACTICAL VEHICLES

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ABSTRACT

Combat operations are suffering from unnecessarily high fuel demand which degrades capability, exposes support operations to greater risk than necessary, and increases operations and support costs. This thesis describes the current suite of hybrid drivetrain technologies, evaluates their effectiveness in a tactical environment, and suggests an architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements. This thesis includes a comprehensive analysis of nine power sources and three general hybrid architectures against ten performance attributes using multiple criterion decision theory with considerations for selection criteria dependencies and vehicle duty cycles. The rating of selection criteria is not always a direct comparison of component performance parameters. In some cases, capabilities are dependent on the general hybrid architecture and on the form of energy storage in others. In a fully burden cost of fuel context, the capability of hybrid drivetrains to improve fuel economy of vehicles by up to 20% translates to \$0.39–\$83.54 billion in annual savings across the Army's tactical wheeled vehicle fleet depending on the fuel delivery method. The recommended hybrid drivetrain architecture is a series hybrid with a diesel engine primary power source, flywheel secondary power source, and permanent magnet traction motors.

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EXECUTIVE SUMMARY

Combat operations are suffering from unnecessarily high fuel demand which degrades capability, exposes support operations to greater risk than necessary, and increases operations and support costs. Recent military operations in countries with underdeveloped infrastructures, such as Afghanistan, have highlighted the issue for operational commanders causing them to request that reducing fuel consumption in tactical vehicles become a top priority for military acquisition programs. This thesis describes the current suite of hybrid drivetrain technologies, evaluates their effectiveness in a tactical environment, and suggests an architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements. This thesis includes a comprehensive analysis of nine power sources and three general hybrid architectures against ten performance attributes using multiple criterion decision theory with considerations for selection criteria dependencies and vehicle duty cycles.

The additive weighting method of decision evaluation theory applied in this thesis provided the capability for the strength of a design concept in one selection criteria to compensate for a weakness in another. The weights given to each selection criteria allowed the user representatives to place higher importance on specific criteria related to improving mission success. The end result was a well-balanced design concept that provided improved performance in many areas and offered additional capability not available with a conventional drivetrain.

The recommended hybrid drivetrain architecture is a series hybrid with a diesel engine primary power source, flywheel secondary power source, and permanent magnet traction motors. This architecture provides many enhanced capabilities over a conventional drivetrain vehicle such as improved operating range, power to weight ratios, energy efficiency, and export power. Additionally, the architecture provides the capability of silent movement. The recommended architecture also provides improvements in all areas of mobility and survivability with the exception of braking and magnetic signatures respectively. The transportability and safety capabilities are mildly

degraded due to additional special training and handling procedures required to handle the stored energy in the flywheel with regards to air transportation and general maintenance and repair.

In a fully burden cost of fuel context, the capability of hybrid drivetrains to improve fuel economy of vehicles by up to 20% translates to an average annual savings per tactical vehicle of 566 gallons and \$0.39–\$83.54 billion in annual savings across the Army’s tactical wheeled vehicle fleet depending on the fuel delivery method. From a system perspective, the recommended hybrid drivetrain architecture is operationally effective, provides improved and new capabilities, with few and easily mitigated degradations in capability. As new technologies emerge and current ones become more efficient and less expensive, the analysis conducted in this thesis should be updated and the architectures re-evaluated.

ACKNOWLEDGMENTS

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I. INTRODUCTION

A. BACKGROUND

During his 2003 tour as Commanding General, 1st Marine Division in Operation Iraqi Freedom, Gen. James T. Mattis was quoted as stating “Unleash us from the tether of fuel” (Defense Science Board Task Force, 2008). In 2006, the Undersecretary of Defense for Acquisition, Technology & Logistics directed the Defense Science Board to form a Task Force to examine the Department of Defense’s energy strategy. The Task Force concluded that Military:

> Operations are suffering from unnecessarily high, and growing, battlespace fuel demand which degrades capability, increases force balance problems, exposes support operations to greater risk than necessary, and increases life-cycle operations and support costs. (Defense Science Board Task Force, 2008)

In response to the growing need to improve tactical vehicle fuel efficiency, the Office of Secretary of Defense initiated the Fuel Efficient Ground Vehicle Demonstrator (FED) program to address energy conservation needs highlighted by the Defense Science Board: Energy Security Task Force. The overarching goal of the program is to improve military vehicle technology to reduce fuel consumption on the battlefield, and reduce the Military’s dependence on oil.

B. PURPOSE

This thesis describes the current suite of hybrid drivetrain technologies, evaluates their effectiveness in a tactical environment, and suggests a hybrid drivetrain architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements.

C. RESEARCH QUESTIONS

1) What hybrid drivetrains architecture provides the best overall performance for tactical vehicles?

   - Refer to Section V.B.3

2) What hybrid vehicle drivetrains exist?

   - Refer to Section II.B. & II.C.

3) How do the hybrid drivetrains perform against vehicle mobility, transportability, survivability, and safety requirements?

   - Refer to chapter IV

4) What elements of a vehicle's architecture have the greatest impact on fuel efficiency of a vehicle?

   - Refer to chapter IV

D. BENEFITS OF STUDY

This thesis provides knowledge that can be used by service requirements developers, tactical vehicle developers, and other military related activities; improving the understanding of the impacts of the integration of hybrid drivetrain architectures within the development of tactical vehicles.

E. SCOPE AND METHODOLOGY

1. Scope

The thesis focuses on current and developmental hybrid drivetrain vehicle technologies and their application to tactical vehicles. The thesis identifies other vehicle architectures and characteristics that affect fuel efficiency, but does not evaluate their impact. Much of the analysis is dependent on evaluations of energy conversion efficiency, energy storage, power to weight ratios, and impacts on requirements (mobility, transportability, survivability, and safety).

2. Methodology

1) Conduct a literature review of the Fuel Efficient Ground Vehicle Demonstrator (FED) program documents, hybrid drivetrain architectures, and other pertinent hybrid technology related material.

- A literature review of work conducted to date on hybrid drivetrain vehicle architectures revealed that the focus was on identifying currently available architectures; capabilities and limitations; and desired areas of technical growth. The main sources cited in this paper are the *Technology Roadmap for the 21st Century Truck Program* report published by the Department of Energy and the *All Electric Combat Vehicles (AECV) for Future Applications* report published by the NATO Research and Technology Organization. This thesis fulfills a gap in research for recommending hybrid drivetrain architectures for tactical vehicle applications. Research in this thesis expands upon the capabilities and limitations of currently available drivetrain architectures and applies systems engineering methodologies to suggest a hybrid drivetrain architecture that would provide the best overall performance for a tactical vehicle.

2) Conduct a review of hybrid drivetrain related technology studies and technology demonstrators.

3) Interview ground vehicle requirements developers to determine what tradeoffs the user community would be willing to make for better fuel efficiency.

4) Research current fuel consumption performance of a typical tactical vehicle (i.e., HMMWV).

5) Evaluate the impacts of the integration of hybrid drivetrain technologies to tactical vehicles.

6) Develop recommendations for improving tactical vehicle fuel efficiencies by applying hybrid drivetrain technologies to the vehicle architecture.

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II. HYBRID DRIVETRAIN ARCHITECTURE BACKGROUND

A. INTRODUCTION

1. Vehicle Characteristics that Affect Fuel Efficiency

The fuel efficiency of a vehicle is an attribute of the overall system, with each subsystem contributing to the overall performance. A motor vehicle as a system is inefficient from an energy conversion perspective. A motor vehicle consists of a large number of moving parts required to propel the vehicle, each of which contribute to a loss of energy including the vehicle body itself (see Figure 1). The following sections will briefly discuss the characteristics of a vehicle that affect the overall energy efficiency of the system.

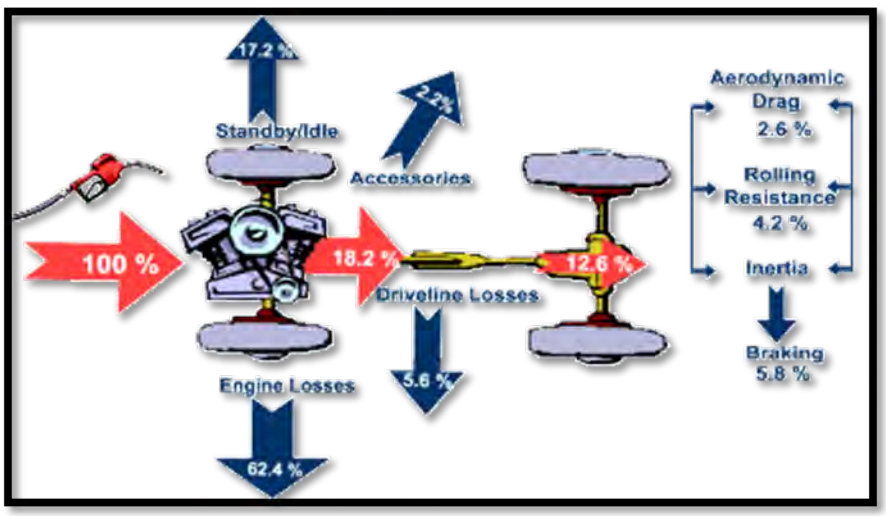

Figure 1. Fuel Energy Losses in a Gasoline-Powered Vehicle. (From Energy, 2010)

a. Engine Efficiency

One of the most inefficient subsystems in a vehicle is the engine. Thermodynamic (chemical to mechanical energy conversion) efficiencies for engines range from 25–30 percent for gasoline engines to 40–45 percent for diesel engines (21st Century Truck Program, 2000). When comparing the actual measured thermal efficiency of a diesel engine to the ideal operating cycle, there are five mechanisms that account for

the sixty percent loss of efficiency: combustion (22.5%), exhaust (14.4%), heat transfer (13.5%), aerodynamic "pumping losses" (4.7%), and mechanical friction (4.8%) (Heywood, 1988).

b. Tire Rolling Resistance

The primary road load on a tactical vehicle such as a HMMWV from zero up to 30 mph (60 mph for a typical passenger vehicle) is the tire rolling resistance (see Figure 2 and Figure 3), after which the aerodynamic resistance becomes the primary force (Gillespie, 1992). Unlike other loads on a vehicle that act only under certain conditions of motion, rolling resistance is present from the instant the wheels begin to rotate and remains effectively constant throughout the range of speed. There are several factors that affect the rolling resistance of a tire: mainly the tire temperature, inflation pressure, load, speed, material, and design. A large portion of the energy consumed in a rolling wheel is converted into heat within the tire due to material deflection and tire slip. Typical tire temperatures will rise up to 80 degrees before reaching equilibrium at the operating temperature (Gillespie, 1992). The rise in tire temperature increases the inflation pressure, often rising up to four psi. The effect of tire inflation pressure and load on rolling resistance is dependent on the surface type the vehicle is traveling over. For medium hard soil, like a dirt road, the tire inflation pressure has a negligible effect on rolling resistance. On hard paved surfaces, rolling resistance decreases by up to 75 percent as the tire inflation pressure increases from 10 to 40 psi (Gillespie, 1992). On soft surfaces, such as sand, rolling resistance can increase up to 50 percent when the inflation pressure is raised from 10 to 40 psi (Gillespie, 1992). The direct relationship between inflation pressure and rolling resistance on soft surfaces is why the military uses a central tire inflation system (CTIS) on tactical vehicles to adjust tire pressures according to the terrain. The reduction in rolling resistance resulting from lowering the tire pressure in sand decreases the ground penetration, and effectively lowers the ground pressure, making it easier to travel over the terrain (Gillespie, 1992). The effect of speed on rolling resistance is negligible below 60 mph. Above 60 mph, rolling resistance increases and becomes the primary factor determining a tire's speed rating. The material makeup can have a significant effect on rolling resistance. A slick racing tire can have up

to a 20 percent lower rolling resistance compared to a treaded tire (Gillespie, 1992). Rubber compounds also affect rolling resistance. Changes in the softness of the rubber will have a proportional effect on rolling resistance, increasing as the rubber compound used is softer and decreasing as harder rubber compounds are used. The size and construction of the tire can affect rolling resistance in multiple ways. Using tires with lower aspect ratios will lower the rolling resistance and tires with reinforced sidewalls can decrease the rate at which rolling resistance increases above 30 mph for a tactical vehicle such as the HMMWV (Gillespie, 1992).

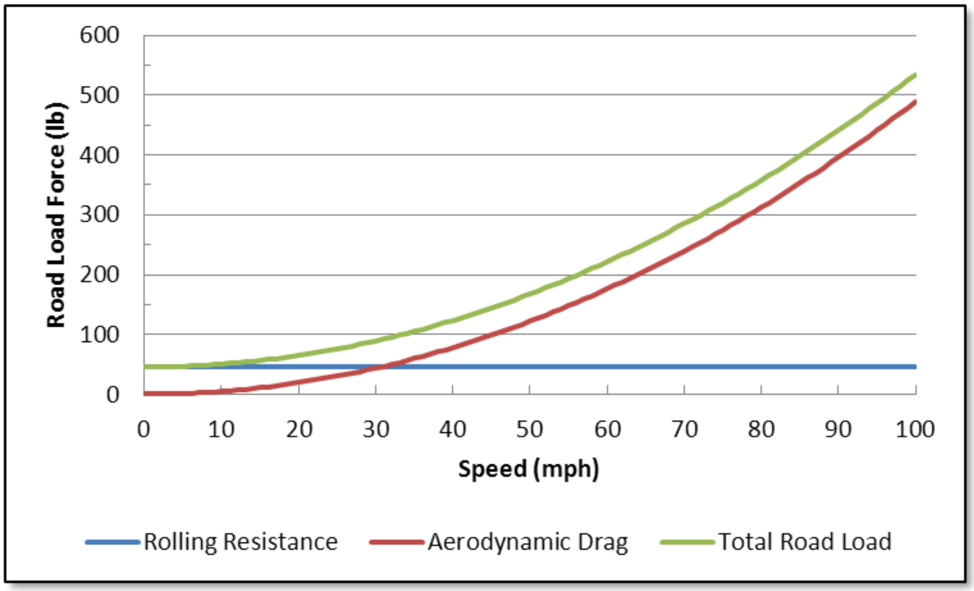

Figure 2. Road load for HMMWVM1097 A2.
(After 21st Century Truck Program, 2000)

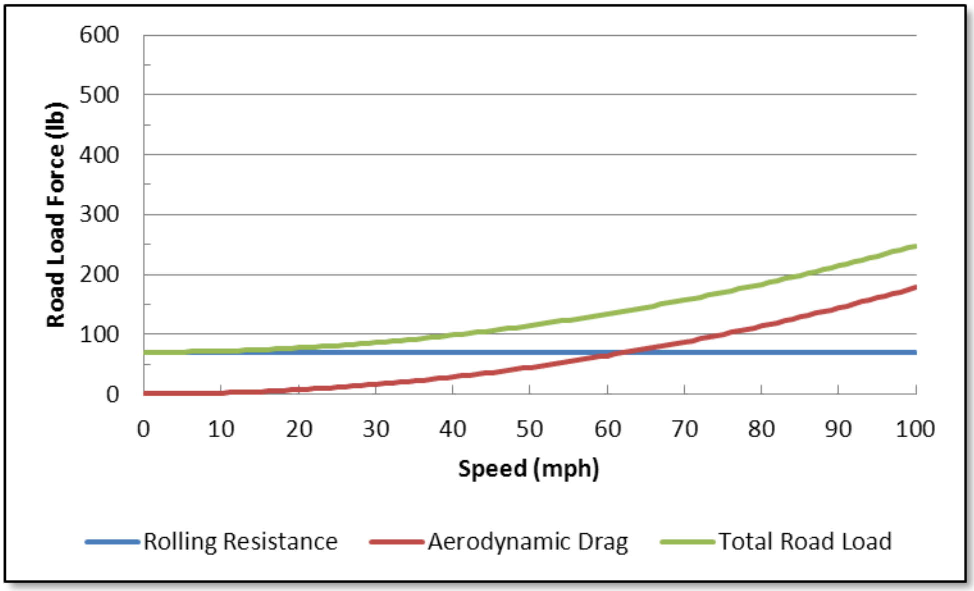

Figure 3. Road load for a typical passenger car (1995 Saturn SL2). (After Lumkes, 2002)

c. *Aerodynamic Drag*

The primary road load on a tactical vehicle such as a HMMWV above 30 mph (60 mph for a typical passenger vehicle) is the aerodynamic resistance, also known as aerodynamic drag (see Figure 2 and Figure 3). The drag force on a vehicle increases with the square of the speed of the vehicle. The two main characteristics of a vehicle that contribute to aerodynamic drag are the frontal area and drag coefficient. The frontal area of the vehicle has a direct relationship to the aerodynamic drag on the vehicle. A certain percentage reduction in the frontal area of a vehicle will result in an equal percent reduction in the aerodynamic drag force. A change in the shape of the vehicle frontal area can also affect the amount of aerodynamic drag on the vehicle by varying the location of the stagnation point. The drag coefficient of a vehicle is determined experimentally from wind tunnel tests and is a ratio of the drag force to the product of the dynamic pressure and vehicle frontal area. The drag coefficient is mainly a factor of the overall shape of the vehicle with the greatest contribution coming from the vehicle afterbody (rear roof edge to rear of vehicle), wheels, and wheel wells (Gillespie, 1992). Besides aerodynamic forces affecting fuel economy by requiring horsepower to

overcome them, aerodynamic drag also affects the handling of the vehicle by imposing rolling, pitching, and yawing moments on the vehicle.

d. Vehicle Weight

When considering the modes of operation for a vehicle, acceleration is the largest contributor to fuel consumption. This is generally why a vehicle achieves better fuel economy while maintaining a constant speed during highway driving, versus the repeated accelerations made during city driving. The main characteristic affecting acceleration performance is the vehicle weight or more specifically the power-to-weight ratio. Effectively to maintain the same acceleration performance, the heavier the vehicle is, the more horsepower it requires, generally resulting in a larger or higher fuel consumption engine.

e. Drivetrain Losses

As illustrated in Figure 1, the drivetrain of a vehicle can contribute to a signification reduction in the energy efficiency of the vehicle. The typical energy loss in a vehicle drivetrain system is 15–20 percent. The source of the energy loss comes from the torque required to accelerate the inertia of the rotating drivetrain components; seal and bearing drag; and gear windage and friction. The addition of four-wheel-drive; typical of a military vehicle; adds the need for a transfer case and the upsizing of drive shafts and drive axles generally resulting in drivetrain losses closer to the 20 percent range.

f. Engine Idling

The stationary idling of a vehicle engine wastes a significant amount of energy with respect to the range and fuel economy. The fuel consumed while a vehicle is idling is primarily used to power the coolant pump, water pump, oil pump, compartment fans, engine management systems, and the electronic control unit with the remaining energy being dissipated as heat through the exhaust system.

g. Vehicle Accessories

The serpentine belt driven vehicle accessories (air conditioning compressor, alternator, cooling fans, and pumps) are of particular interest with regards to fuel efficiency because they are a constant draw on the vehicle power even when they are not in use. They are also directly dependent on the operating speed of the engine, and therefore, are not necessarily optimized for their own efficient operation. The operation at variable engine speeds forces designers to make compromises, resulting in larger, heavier, and less-efficient components compared to operation at an optimum or discrete speed.

h. Braking

While not directly contributing to the fuel consumption of a vehicle, braking reduces the energy efficiency of the vehicle system by converting the vehicles' kinetic energy into unusable heat. In urban driving, braking can waste one-half or more of the total energy that the engine is able to transmit to the wheels (21st Century Truck Program, 2000). The energy efficiency of the braking system is dependent on the vehicle weight, aerodynamic drag, and the brake force distribution between the front and rear axles.

B. FULL HYBRID DRIVETRAIN ARCHITECTURES

A hybrid drivetrain is a propulsion system that provides more than one source of power for the vehicle. This leads to two main classifications of hybrids, mild and full hybrids. The architecture of a full hybrid vehicle drivetrain is classified into two general types: parallel and series hybrids. Both of the basic full hybrid types share many of the same components; however the orientation of the components differs relative to the driven wheels of the vehicle (see Figure 4). Figure 4 depicts the differences in power coupling for a series hybrid (a), parallel hybrid (b), series-parallel hybrid (c), and a complex hybrid (d). For the purpose of this paper, the discussions of full hybrids will be limited to the two basic types (series and parallel) and not combinations thereof.

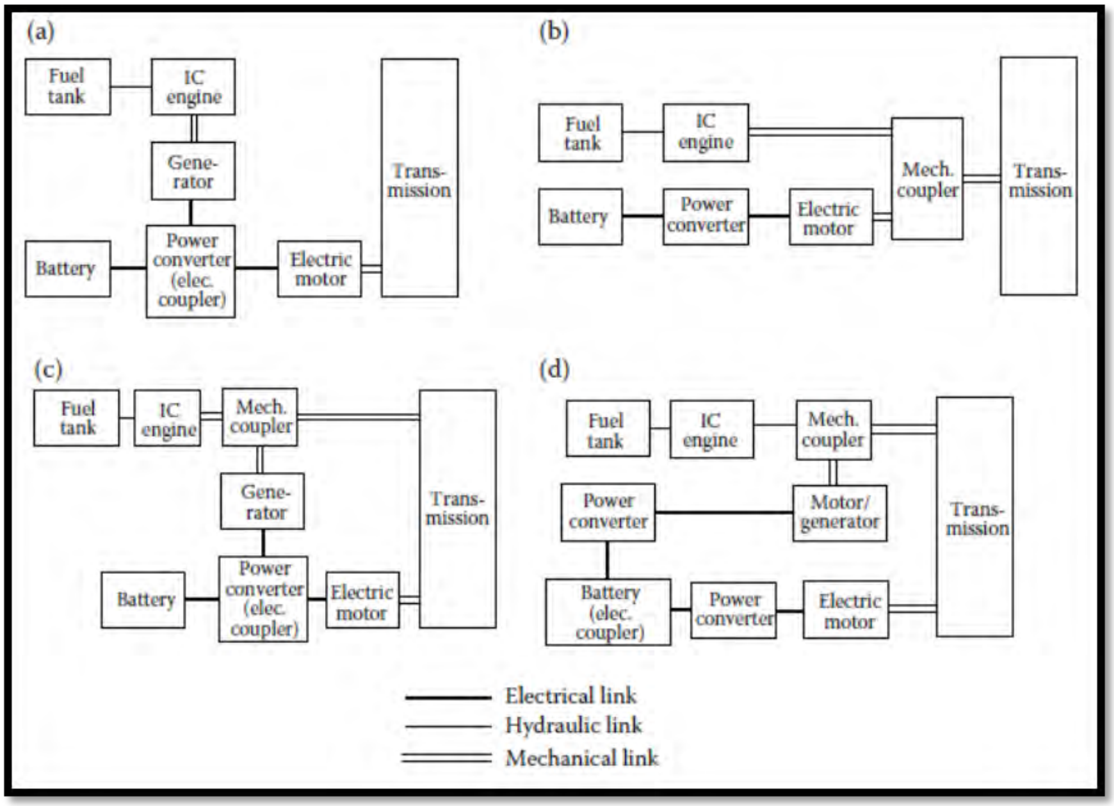

Figure 4. Hybrid Drivetrain Classification. (From Ehsani, Gao, & Emadi, 2010)

With every drivetrain configuration there are advantages and disadvantages to the selection of various components within the system. The selection of those components and their integration can vary wildly depending on the desired performance characteristics for the overall system. The following sections will summarize the vehicle and performance characteristics associated with the different types of hybrid drivetrains.

1. Parallel Hybrid

In a parallel hybrid drivetrain the engine supplies mechanical power directly to the wheels while being assisted by an electric motor mechanically coupled to the drivetrain. This arrangement is known as a mechanical power coupling drivetrain system. In a parallel hybrid vehicle the wheels may be driven by the engine, the electric motor, or the combined power of them both. The main differences between a

conventional drivetrain and a parallel drivetrain are the addition of an electric motor mechanically coupled to the engine, a motor controller, and a power converter (see Figure 4 and Figure 5).

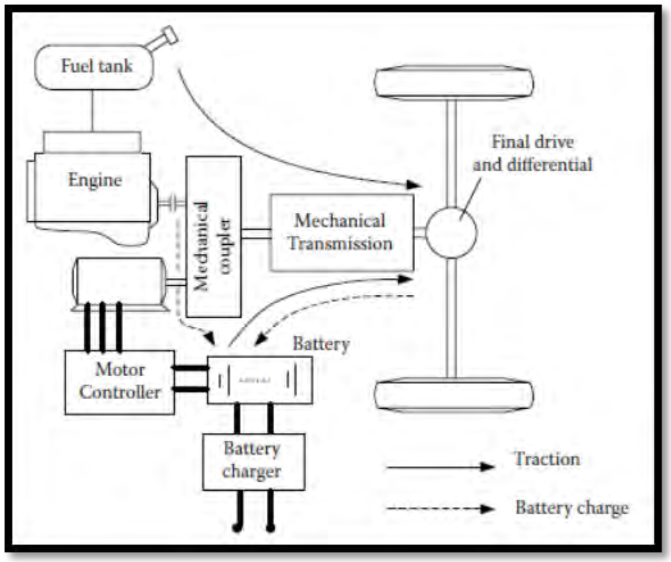

Figure 5. Parallel Hybrid Electric Drivetrain Configuration. (From Ehsani, Gao, & Emadi, 2010)

The advantages of a parallel hybrid drivetrain over a series hybrid are: fewer energy form conversions, a smaller traction motor, elimination of the need for an auxiliary generator, and a smaller secondary power source (Ehsani, Gao, & Emadi, 2010). The parallel hybrid drivetrain achieves fewer energy form conversions due to both power sources providing energy directly to the drivetrain, resulting in lower energy losses. To provide energy to the wheels, the internal combustion engine converts chemical energy to mechanical, while the electric motor converts electrical energy into mechanical, each changing form only once. The traction motor is smaller because power from the engine is combined with the electric motor to provide vehicle propulsion, resulting in lower power requirements for the traction motor (21st Century Truck Program, 2000). The auxiliary generator can be eliminated by using the internal combustion engine for supplemental recharging of the secondary power source. The secondary power source itself is comparatively smaller than what is used in a series hybrid as a parallel hybrid relies more on regenerative braking. Regenerative braking

(see Section II.C.1.) captures the vehicle's kinetic energy and directs it to an energy storage device, reducing the need to store as much energy onboard. Finally, the parallel hybrid is more efficient during highway driving conditions compared to urban stop-and-go due to load sharing between the electric motor and an internal combustion engine operating at steady state speeds.

The mechanical power coupling arrangement in a parallel hybrid drivetrain imposes a number of disadvantages from a vehicle characteristic standpoint. The mechanical coupling between the engine and the driven wheels requires the internal combustion engine to work over a range of speeds, thereby not making it possible to optimize the efficiency of the engine by operating it in its most efficient operating condition. The mechanical coupling of the engine and electric motor with the drivetrain also results in a larger number of vehicle components, leading to a more complex system. The increased complexity adds cost in developing the control systems and weight in increasing the number of total components in the vehicle. The hybrid components in the Audi Q5 hybrid Quattro midsize sports utility vehicle, for example, add approximately 287 pounds of extra weight to the vehicle (Audi Communications, 2011).

2. Series Hybrid

A series hybrid drivetrain mainly consists of an engine, generator, energy storage device, and traction motors. The engine supplies power to a generator, then power is combined with the secondary power source and fed to a traction motor coupled to the drivetrain. This arrangement is known as an electrical power coupling drivetrain system (Ehsani, Gao, & Emadi, 2010). In this configuration, the wheels are driven directly by traction motors and there is no mechanical link between the engine and the wheels (see Figure 6). By virtue of this configuration, series-hybrid vehicles are able to provide all-electric propulsion (silent propulsion), something parallel hybrids are not capable of. Series hybrids are often considered range-extended electric vehicles because they are electric vehicles that are driven only by electric traction and use an onboard combustion engine as a means of a generator to recharge the secondary power source.

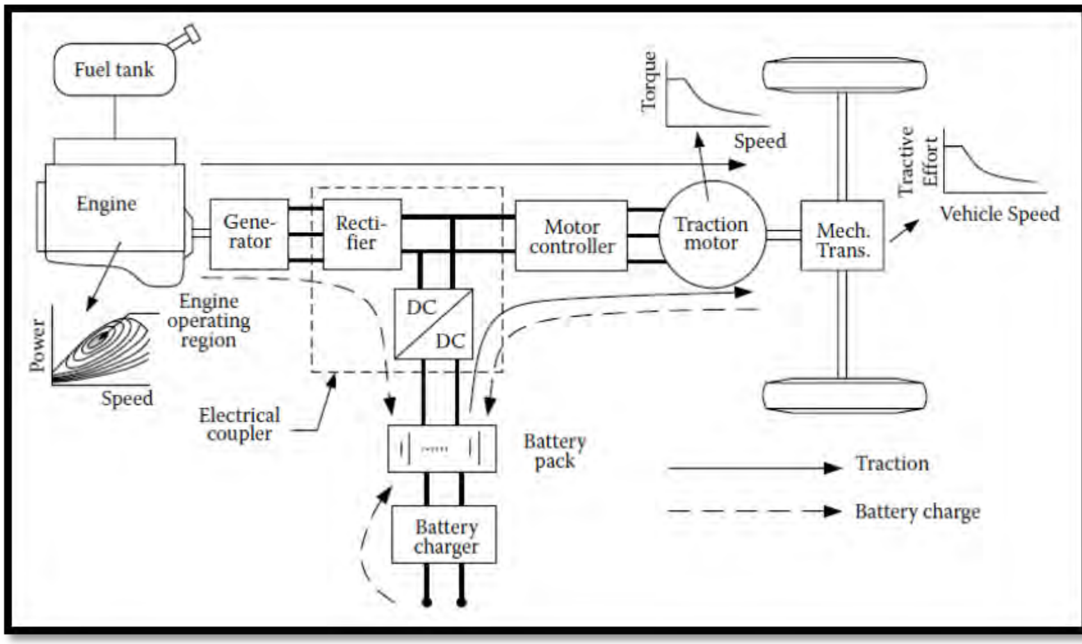

Figure 6. Series Hybrid Electric Drivetrain Configuration.
(From Ehsani, Gao, & Emadi, 2010)

The physical architecture of a series hybrid drivetrain is vastly different than a conventional drivetrain and contains fewer parts than a parallel hybrid. The series hybrid eliminates the torque converter, transmission, transfer case and driveshafts compared to a conventional drivetrain. In their place an electric motor mechanically coupled to the engine, a motor controller, a power converter, one or more traction motors, and a larger secondary power source compared to a parallel hybrid are added.

There are a number of advantages of the series hybrid architecture. By decoupling the engine from the wheels, the engine is able to run constantly within its maximum efficiency region. Auxiliary systems can also be decoupled from the engine, adding to the overall efficiency of the hybrid system. Energy losses in the drivetrain can be further reduced by removing the mechanical differential and using two traction motors each powering a single wheel. This offers more flexible packaging options and decouples the speeds of the two wheels. By allowing the speeds of the two wheels to be independently managed, the pair of traction motors improves the vehicle handling characteristics by performing a function similar to that of a mechanical limited slip differential or conventional traction control. Vehicle handling and trafficability can be

further enhanced by placing in-wheel motors at all four wheels. Since the speed and torque of each wheel can be independently controlled, the cornering and off-road performance can be more precisely managed. This is very important for military vehicles which usually operate on difficult terrain, such as cross-country, trails, and soft ground. From an off-road trafficability perspective, the four in-wheel motors can perform the function of differential lockers, allowing all available power to be directed to a single axle or wheel.

The disadvantages of a series hybrid drivetrain are larger traction motors, a larger secondary power source, and an increased number of energy conversions compared to a parallel hybrid. Since the traction motor is the only component directly propelling the vehicle, it must be sized to produce enough power for optimal vehicle performance in terms of acceleration and gradeability. The secondary power source is larger in a series hybrid because it provides all of the energy to turn the wheels; the combustion engine does not contribute to the available tractive power of the vehicle. There are a larger number of energy conversions in a series hybrid because the energy from the engine changes form twice to reach the driven wheels (mechanical to electrical in the generator and electrical to mechanical in the traction motor). The inefficiencies of the generator and traction motor may cause significant losses.

3. Hybrid Power Sources

The architecture of a hybrid drivetrain can be composed in several different ways. The main defining feature of a hybrid architecture is the combination of primary and secondary power sources. The selection of the power sources and the method in which they are integrated into the vehicle determines what type of hybrid is created and the performance characteristics of the vehicle. Figure 7 depicts some of the possible combinations of power sources and energy storage devices that make up mechanical and electric hybrids.

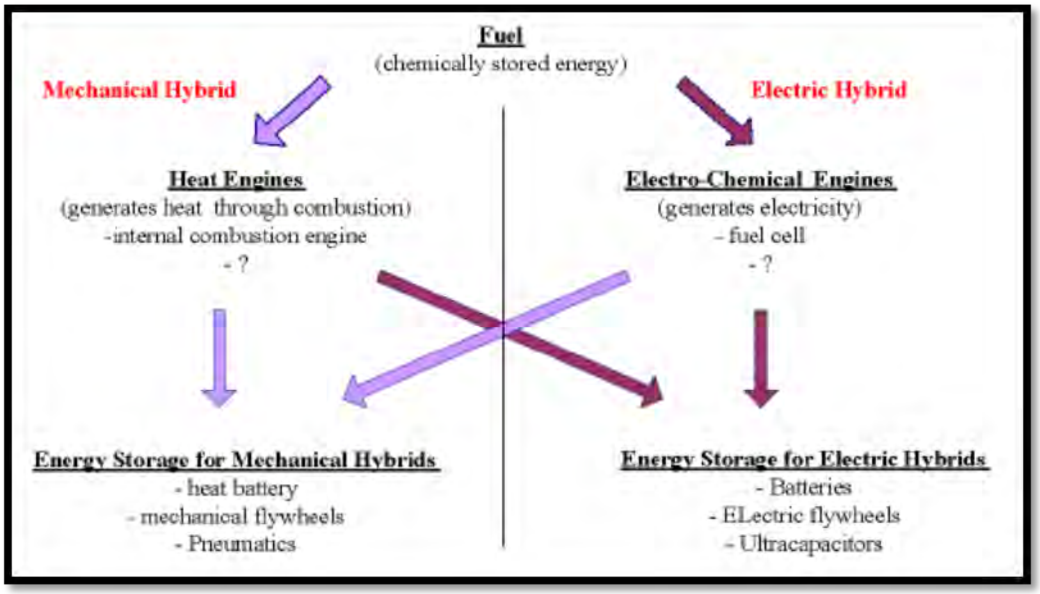

Figure 7. Hybrid Power Source Combinations.
(From 21st Century Truck Program, 2000)

a. Primary Power Sources

The primary power sources employed in hybrid vehicles are generally an internal combustion engine, fuel cell, or a microturbine. To date, nearly every consumer or commercial application of a full hybrid drivetrain has used the internal combustion engine as the primary power source, while the fuel cell and microturbine generally only surface in concept vehicles and technology demonstrators.

A fuel cell is an electrochemical device that generates electricity by harnessing energy from the reaction of hydrogen and oxygen (Figure 8). Although development of fuel cell technology began back in the 1960s when it was first developed for NASA (Ehsani, Gao, & Emadi, 2010), there has not been significant focus on improving the technology over the last several decades until now. There are six major types of fuel cells; the proton exchange membrane fuel cell (PEMFC), molten carbonate fuel cell (MCFC), solid oxide fuel cell (SOFC), phosphoric acid fuel cell (PAFC), alkaline fuel cell (AFC), and the direct methanol fuel cell (DMFC) (Ehsani, Gao, & Emadi, 2010). Of the six major types of fuel cells; the PEMFC, SOFC, and AFC are applicable for use as primary or secondary power sources for vehicles; with the

automotive industry focusing its efforts on the development of the PEMFC (21st Century Truck Program, 2000). There are a number of advantages of using a fuel cell as the primary power source for a vehicle. All fuel cells can use pure hydrogen or reformed hydrocarbon fuels such as gasoline, diesel, methanol, ethanol, or natural gas as fuel. Because the fuel cell converts the chemical energy of a fuel into electrical energy without combustion, the process is highly efficient (up to 70%) and extremely clean (21st Century Truck Program, 2000). The fuel cell runs at its highest efficiency when fueled by pure hydrogen. When reformed hydrocarbon fuels are used, the overall subsystem efficiency is reduced. Another distinct advantage of a fuel cell is that there are no toxic emissions when they are fueled by pure hydrogen, with the electrochemical reaction only producing heat and water.

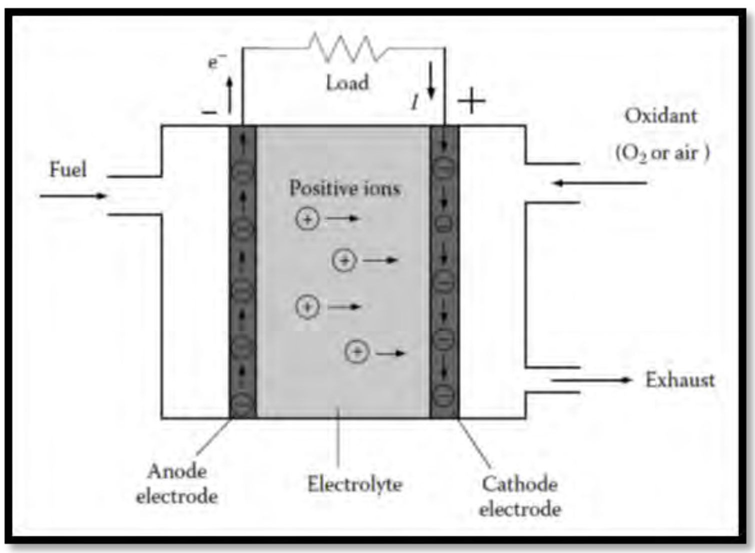

Figure 8. Basic operation of a fuel cell.
(From Ehsani, Gao, & Emadi, 2010)

The barriers to the application of fuel cell technology to vehicles are resolving safety issues with the storage of pure hydrogen fuel and improving the energy density. The downside to achieving the highest efficiency in a fuel cell is that it requires the storage of hydrogen in either a high pressure tank in a compressed state or in a heavily insulated tank in a liquid state. To achieve energy densities nearly equivalent to gasoline, hydrogen would need to be compressed to several hundred atmospheres, which

poses a safety issue in the event of a crash in which the tank could explode and requires reinforced storage tanks that would increase system weight and subsequently reduce energy density (Ehsani, Gao, & Emadi, 2010). However, there is a trade-off between increased efficiency and power density. To improve the overall energy efficiency of the fuel cell, higher voltages are required which result in the fuel cell operating at lower power densities. Consequently, the size of the fuel cell stack would have to be increased to meet vehicle power demands (21st Century Truck Program, 2000).

The military has employed gas turbine engines as the primary power source in tanks, such as the Abrams, and naval vessels since the 1950s. The gas turbine engine is a continuous internal combustion rotary engine. The gas turbine operates by fuel being supplied to a burner and burned with an excess of compressed air in what is known as a lean burn. The hot combustion gases then expand and pass through a turbine, which generates power and is transferred to the output shaft, as shown in Figure 9 (Capehart, 2010). Advances in materials and control technologies have enabled the miniaturization of gas turbines, resulting in the introduction of microturbines. The use of microturbines in a hybrid drivetrain application has several advantages. When a microturbine is selected as the primary power source for a series hybrid architecture, the speed decoupling between the primary power source and the wheels allows the microturbine to run at a constant speed and within its optimum fuel consumption range. For a typical microturbine, the ideal operating speed is generally between 80,000-100,000 revolutions per minute (rpm). By operating at such high speeds, the output from a microturbine can be matched to smaller high speed generators, thus reducing the weight and size of the primary power unit (RTO Applied Vehicle Technology Panel (AVT), 2004). The size and operating characteristics of a microturbine allow it to run without a cooling system, thereby improving noise and thermal signatures as compared to a diesel engine (RTO Applied Vehicle Technology Panel (AVT), 2004). Another advantage for military applications is the ability of the microturbine to run on a variety of fuels; such as natural gas, hydrogen, propane, diesel, and others; making it less dependent on the quality of the fuel as compared to a fuel cell or diesel engine (Brockbank, 2008). The

continuous combustion in the microturbine also results in a lower visual signature due to reduced emissions compared to a standard internal combustion engine.

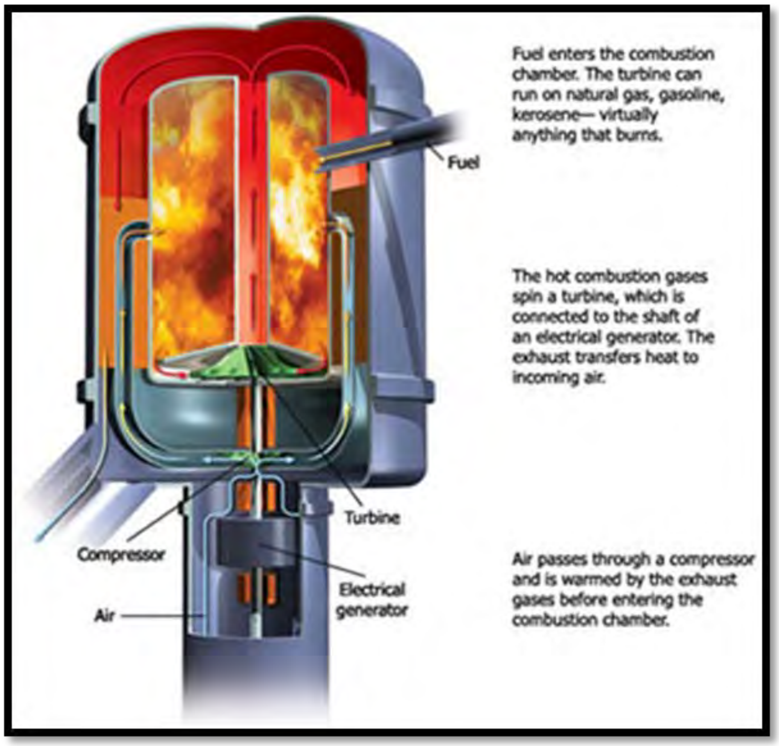

Figure 9. Microturbine engine operation. (From Capehart, 2010)

The implementation of a microturbine in a military tactical vehicle encounters a few challenges in the areas of high altitude operation, expensive materials/manufacturing processes, and immature technologies. When operating at high altitudes a microturbine losses power due to a reduction in the mass of air entering the inlet, as compared to operation at sea level. To compensate for the richer air/fuel mixture the fuel injection rate would need to be reduced to lean out the burn. The high rotating speeds and continuous combustion of a microturbine require the use of more exotic materials and manufacturing processes to handle the stresses in the turbine blades and the continuous high temperatures seen in the combustion chamber. Finally, the technology to support microturbines has only been around for about a decade and they have not gained widespread acceptance in the marketplace due to the higher costs and reduced efficiencies when used as the sole power source for a vehicle. That, coupled with the continuing work on improvements to the manufacturing process to reduce the cost and

improvements to the integration with hybrid drivetrains places the technology readiness level for a microturbine between five and six. Further development is needed in these areas to make the microturbine viable for production use, until then it proves to be a promising technology for future vehicle applications.

b. Secondary Power Sources

To complete the concept of a hybrid drivetrain, a secondary power source is required to supply energy to the drivetrain via electrical or mechanical means. The combination of the primary and secondary power sources chosen will determine if the vehicle is considered to have an electro-mechanical, full mechanical, or full electric hybrid drivetrain. The common factor across all three types is that the primary power sources run on fuel. The main purpose of the secondary power source is to supplement the primary power source, enabling its size to be reduced or it to operate within an optimal efficiency range.

An electro-mechanical hybrid drivetrain is most likely to consist of an internal combustion engine mechanically coupled to an integrated starter generator, which in turn is electrically coupled to an energy storage device such as a battery, ultracapacitor, or an electric flywheel. The integrated starter generator (ISG) combines the functions of the starter and alternator into a single unit and converts energy from the storage device into power to crank the engine over to enable it to start. The ISG is also capable of automatically shutting down and restarting the engine when the vehicle comes to a stop. This technology is known as a start-stop system and is employed to reduce fuel consumption by reducing the amount of time the engine idles. Under acceleration the ISG uses this power to assist the main power source in propelling the vehicle. During braking, the electric motor in the ISG works as a generator to recharge the energy storage device. This is a form of regenerative braking which will be discussed in further detail in Section II.C.1 along with the different types of electrical energy storage devices (battery, ultracapacitor, and electric flywheel) in Section II.C.2.

A full mechanical hybrid drivetrain consists of an internal combustion engine mechanically coupled to a mechanical flywheel or a hydraulic pump and a set of

accumulators. The operation of the mechanical flywheel will be discussed in Section II.C.2. The operation of a hydraulic hybrid will be described in this section, but will not be evaluated in this paper due to the limited amount of available data.

A hydraulic mechanical hybrid consists of a hydraulic pump/motor, a high pressure accumulator, and a low pressure accumulator. In a series hybrid configuration (Figure 10), the hydraulic pump/motor is mechanically coupled to the internal combustion engine. Under acceleration, the pump draws fluid from the high pressure accumulator and supplies it to a hydraulic drive assembly to rotate the wheels (U.S. EPA, 2010). The fluid is then transferred to the low pressure accumulator where it is stored until it is needed to supply fluid to the pump/motor for either pressurizing the high pressure accumulator or directly powering the drive assembly. In a parallel hybrid configuration (Figure 11), the hydraulic drive pump/motor is attached to the driveshaft and assists in stopping and accelerating the vehicle. Under acceleration, the hydraulic fluid in the high pressure accumulator supplies torque to assist in rotating the driveshaft through the use of the pump/motor (acting as a motor), easing the power burden on the internal combustion engine. The low pressure fluid is then transferred back to the high pressure accumulator for later use by using the rotating energy from the wheels during braking, along with the pump/motor acting as a pump (U.S. EPA, 2010). By absorbing a portion of the rotating energy from the wheels, the hydraulic pump/motor allows the friction brakes to perform less work, thus allowing for the possibility of reducing the brake size and lowering the unsprung mass of the vehicle.

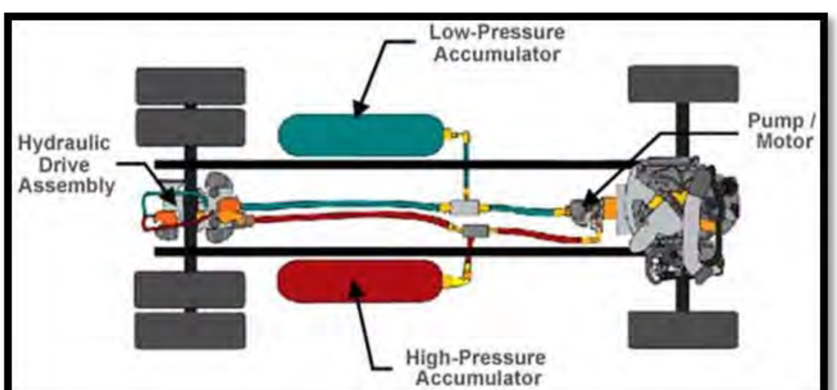

Figure 10. Series Hydraulic Hybrid. (From U.S. EPA, 2010)

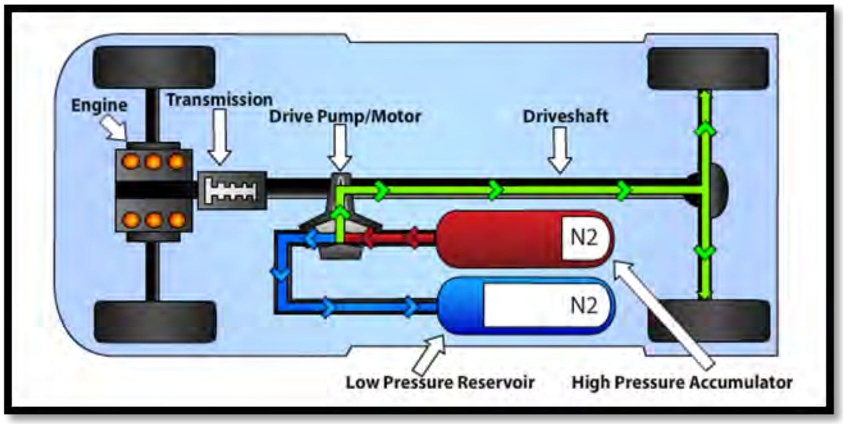

Figure 11. Parallel Hydraulic Hybrid. (From U.S. EPA, 2010)

A full electric hybrid drivetrain combines an electro-chemical engine (fuel cell) with an electrical energy storage device (battery, electric flywheel, or ultracapacitor). The defining characteristic for a full electric hybrid is the output of both the primary and secondary power sources is electricity. Because there are no mechanical couplings between the power sources and the wheels in a full electric hybrid, this combination only exists in the form of a series hybrid architecture.

C. ENERGY RECOVERY SYSTEMS (MILD HYBRID)

Energy recovery systems convert wasted energy such as heat and kinetic energy into useable energy. The energy is either stored electrically, hydraulically, or in the inertia of a flywheel device. A mild hybrid drivetrain architecture consists of a conventional powertrain (internal combustion engine) and the addition of one or more energy recovery or power assist systems (see Figure 12). The use of mild hybrids is most often employed to improve vehicle performance while maintaining the current fuel economy of the vehicle. In this light, mild hybrids are often seen as “power boosters”; however they also include systems to reduce parasitic power losses. While a mild hybrid generally offers the capability to support engine stop-start, it is not capable of pure electric propulsion.

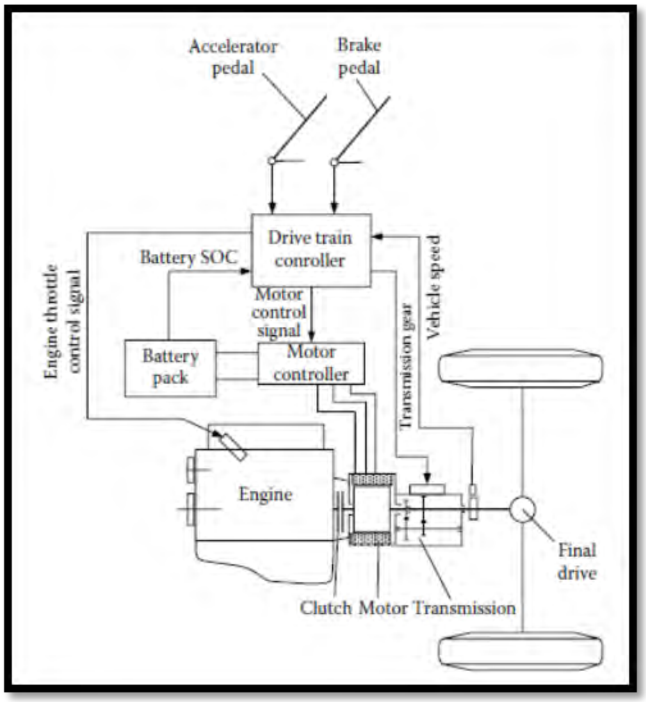

Figure 12. Mild Hybrid Drivetrain Configuration. (From Ehsani, Gao, & Emadi, 2010)

1. Regenerative Braking

The concept of regenerative braking is to capture the vehicle's kinetic energy and direct it to an energy storage device where it can be recovered at a later time in order to increase the operating range of the vehicle. The overall net efficiency of currently available regenerative braking systems is approximately sixty percent (21st Century Truck Program, 2000). The remaining kinetic energy is dissipated through conventional wheel brakes as friction or heat. The use of regenerative braking reduces the need for large friction brakes, allowing them to be physically smaller (21st Century Truck Program, 2000). This reduces the overall vehicle and unsprung weight, while simultaneously improving handling characteristics. The reduction in work required to be performed by the friction brakes to stop a vehicle and the reduction of the size of the brake assembly also reduces the heat signature under deceleration. A regenerative braking system can be incorporated into an electro-mechanical, full mechanical, or full electric hybrid drivetrain. The differentiating factor is whether the pump/motor and the storage device are electrical, hydraulic, or mechanical. In an electric hybrid, the polarity

of the electric motor under braking is reversed (converting mechanical energy into electrical energy), turning it from a drive motor into a generator. The rotation of the motor generates electricity that is transferred to the batteries. In a hydraulic hybrid the energy is recovered using a hydraulic pump to store braking energy in an accumulator to power the vehicle (21st Century Truck Program, 2000). In a mechanical hybrid, the energy is recovered using a continuously variable transmission (CVT) to spin a flywheel. The CVT is then used in reverse fashion to transfer the energy back to the vehicle (21st Century Truck Program, 2000). Regardless of the type of regenerative braking system incorporated in a vehicle, they are most effective at reducing fuel consumption and charging energy storage devices in stop-and-go or hilly driving scenarios.

2. Kinetic Energy Recovery System (KERS)

A kinetic energy recovery system (KERS) is designed to capture the kinetic energy of a vehicle to improve the vehicle's efficiency through enhanced performance with no increase in the energy consumed. A KERS is effectively a regenerative braking system that is used as a power booster to reduce the need to use fuel to accelerate the vehicle, rather than extending the range of a vehicle. Power boosts can range from 80-200 hp depending on the size of the motor and energy storage system (flywheel, battery, or ultra-capacitor) and last for six to eight seconds each time. The boost of power is typically used to accelerate the vehicle from a standstill or in an overtaking maneuver, both driving conditions that consume large amounts of energy.

a. Mechanical Flywheel KERS

A mechanical flywheel consists of a rotating mass (rotor) to store energy, a continuously variable transmission (CVT) to control and transfer the energy to and from the drivetrain, and a containment housing in which the flywheel spins within a vacuum on magnetic bearings to reduce aerodynamic and frictional losses (see Figure 13 and Figure 14). The storage capacity of a mechanical flywheel is dependent upon the mass / inertia and the speed of the flywheel (Ehsani, Gao, & Emadi, 2010). Therefore, either a large, low speed flywheel or a small, high speed flywheel can be used. Since rotational energy increases with the square of speed, it is more advantageous to use a

small high speed flywheel in a tactical vehicle from a weight and space claim perspective. Mechanical flywheels offer exceptional power-handling capabilities (2,000–10,000 W/kg) with low-to-moderate specific energy (10–150 Wh/kg); therefore, flywheels are best suited for applications that demand high power levels and relatively low energy storage, such as a "power-assist" parallel hybrid vehicle (Ehsani, Gao, & Emadi, 2010). In comparison to a battery system, flywheels provide significant advantages in the areas of calendar life, cycle life, efficiency, consistent performance at different temperatures and different ages, and ease of measurement of state of charge (21st Century Truck Program, 2000). A mechanical flywheel also has fewer energy conversions than an electrical system allowing it to be up to twice as efficient at 70% (Brockbank, 2008). The reason behind the higher efficiency is that the energy being recovered, stored, and reapplied to the drivetrain remains in the same energy state (mechanical). A mechanical flywheel combined with a CVT transmission is about half the weight, half the space claim, and a quarter of the cost compared to a comparable battery system (Brockbank, 2008). For example, a mechanical flywheel KERS system being developed in a Jaguar XF sedan that delivers approximately 80 horsepower for up to seven seconds weighs 143 lbs (Kong, 2010).

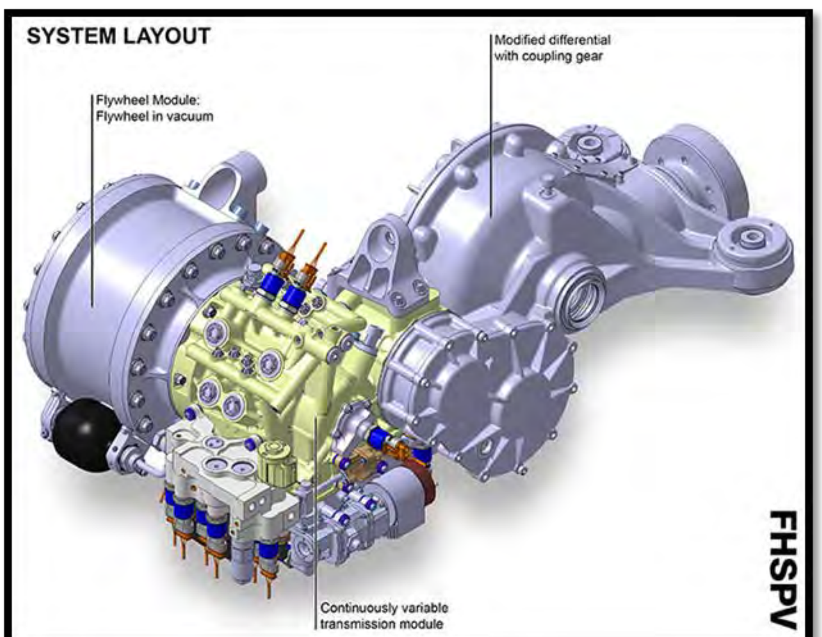

Figure 13. Jaguar XF Mechanical Flywheel System. (From Squatriglia, 2010)

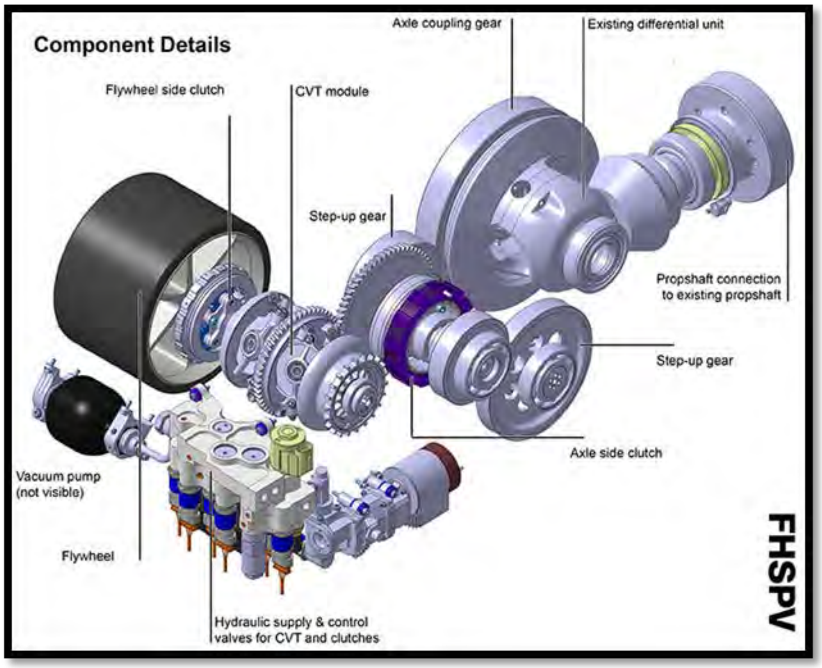

Figure 14. Jaguar XF Mechanical Flywheel System–Component View. (From Squatriglia, 2010)

In a tactical vehicle application the mechanical flywheel suffers from two main problems; gyroscopic forces and the sudden release of energy when the system is damaged. The high rotational speed of the flywheel has a secondary effect of reducing the maneuverability of the vehicle when it changes direction during turning or while ascending or descending grades (Ehsani, Gao, & Emadi, 2010). In the event of damage to a mechanical flywheel as a result of a combat attack, the stored energy will be released in a very short time, potentially producing secondary projectiles and damage to the vehicle and injury to the occupants. For example, if a flywheel capable of storing 1-kWh of energy breaks apart in one to five seconds, it will generate a power of 720–3600kW (Ehsani, Gao, & Emadi, 2010). To reduce the likelihood of damage or injury, there are two main methods of controlling the energy dissipation. The first method is to use a composite flywheel which will fail by delaminating, making it easier to contain (Ehsani, Gao, & Emadi, 2010). The second method is to create a mechanical fuse by enlarging the rim thickness. This will create a neck area just before the rim and will break before the rest of the rotor fails (Ehsani, Gao, & Emadi, 2010). The advantage of this is that only

the mechanical energy stored in the rim needs to be dissipated, rather than the energy stored in the entire rotor (Ehsani, Gao, & Emadi, 2010).

b. Electro-Mechanical Flywheel KERS

The concept and operation of the electro-mechanical flywheel is similar to a mechanical flywheel with the exception that the input and output energy is in the form of electrical energy. To accomplish this, the flywheel rotor has magnetic material embedded in it and surrounds a motor/generator comprised of permanent magnet motors (21st Century Truck Program, 2000). During regenerative braking, electrical energy is transferred through the power electronics to the stator, which in turn spins the rotor, storing the energy in a mechanical state (see Figure 15). During release of the stored energy, the power electronics reverse the flow of electricity and the system acts as generator, transferring the mechanical energy from the rotor to electrical energy in the stator. The energy in the stator is conditioned in the power electronics and transferred to traction motors through high-voltage cables (see Figure 16). The electro-mechanical flywheel suffers a reduction in efficiency due to the need to change energy states multiple times during operation, but otherwise offers the same advantages and disadvantages as the mechanical flywheel.

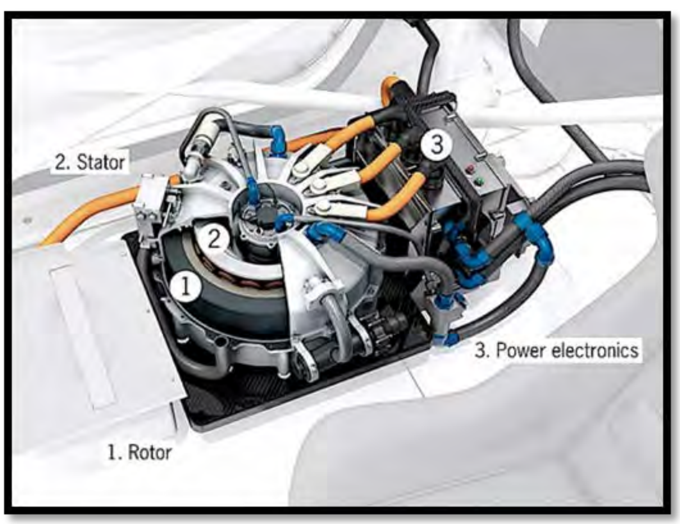

Figure 15. Porsche GT3 R Hybrid–Electric Flywheel KERS Components. (From Abuelsamid, 2010)

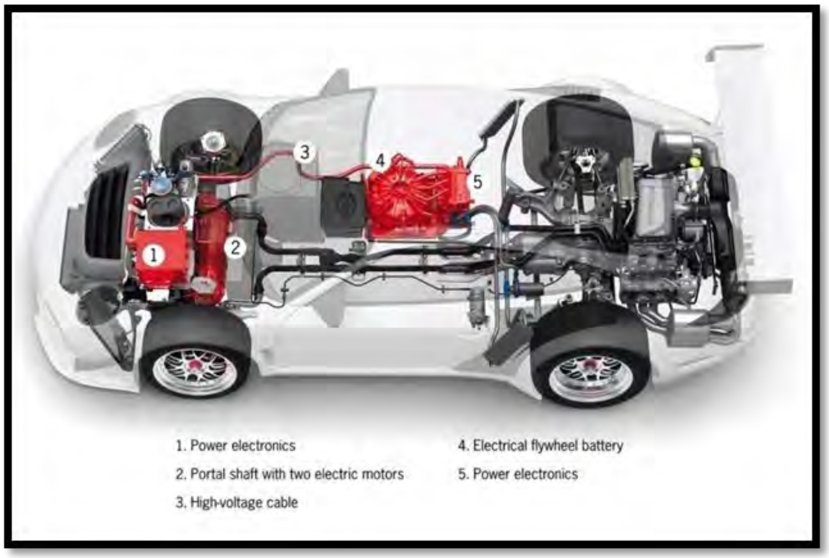

Figure 16. Porsche GT3 R Hybrid–Electric Flywheel KERS Integration. From Porsche AG, 2010)

c. Chemical KERS

A chemical KERS stores the recovered kinetic energy from a regenerative braking system in a chemical state. The energy is stored by charging either a battery pack or a bank of ultracapacitors. In a battery the energy is stored electrochemically when a voltage is applied and the reaction products are converted back to fuel and oxidant (RTO Applied Vehicle Technology Panel (AVT), 2004). In essence, this chemical reaction charges the battery. Power is returned to the vehicle when a current is drawn and electrons flow from the anode through the electrolyte to the cathode (see Figure 17).

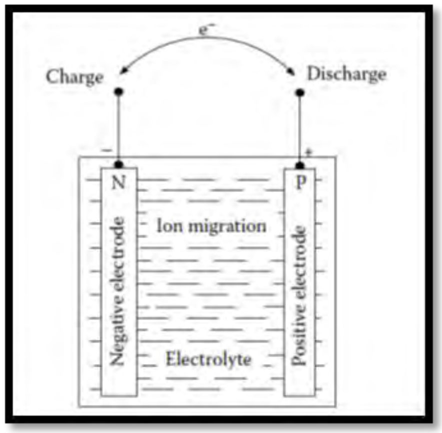

Figure 17. Battery Components and Basic Operation. (From Ehsani, Gao, & Emadi, 2010)

The most common types of batteries used in a hybrid vehicle application are lead-acid, Nickel-metal hydride (NiMH), and Lithium-ion (Li-Ion). Each battery type has successively higher specific power and specific energy capabilities (see Table 1 and Table 2). Lead acid batteries excel in areas of low cost, mature technology, and having a recycling infrastructure in place; but suffer from poor cold temperature performance and potential safety issues from the highly corrosive sulfuric acid inside (21st Century Truck Program, 2000). From a safety perspective, NiMH batteries perform better than lead acid batteries by having good abuse tolerance, being non-toxic, and free of carcinogens (Ehsani, Gao, & Emadi, 2010). The NiMh battery also benefits from fast recharge rates. The challenges for NiMH batteries are that the components are recyclable, but a recycling infrastructure is not yet in place; they have high self-discharge rates; and can be exothermic during charging (21st Century Truck Program, 2000). Lithium Ion batteries offer lower self-discharge rates than NiMH, similar good high-temperature performance and technology maturity, but suffer from lower abuse tolerances (21st Century Truck Program, 2000).

In an ultracapacitor, the energy is stored electrostatically by polarizing an electrolytic solution (see Figure 18) (National Renewable Energy Labratory, 2009). The absence of a chemical reaction to store the energy allows the ultracapacitor to be charged and discharged hundreds of thousands of times resulting in a much higher calendar life

compared to a battery system. Since the ultracapacitor does not have to wait for slow chemical reactions, it can discharge energy faster and with more power than a battery, allowing it to rapidly absorb, store, and release recovered braking energy. The ability to quickly release energy makes the ultracapacitor ideal for assisting tactical vehicles in delivering peak power loads needed for acceleration or hill climbing on rough terrain (Brecher, 2010). The disadvantage of an ultracapacitor is the relatively low energy storage compared to a battery (see Figure 19).

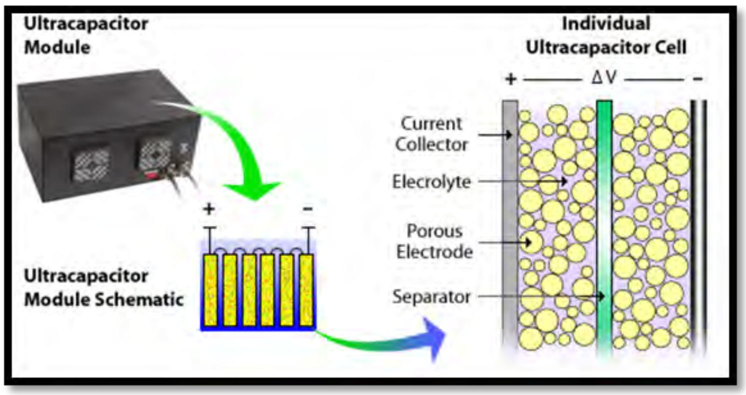

Figure 18. Ultracapacitor Components.
(From National Renewable Energy Labratory, 2009)

D. CHAPTER SUMMARY

The net fuel efficiency of a tactical vehicle is highly dependent on the physical characteristics and performance of each vehicle subsystem individually and as a whole. Reductions in fuel economy can be attributed to efficiency losses (engine and drivetrain), road loads (tire rolling resistance and aerodynamic drag), loss of inertia (braking), vehicle accessory loads, and weight. Alternatively, improvements in fuel economy can be obtained by the integration of mild or full hybrid drivetrain systems consisting of kinetic energy recovery systems or parallel or series hybrid drivetrain configurations respectively. Apart from adjustments to the vehicle physical characteristics, the selection of primary and secondary power sources in combination with an energy storage device can result in marked improvements in fuel economy when the appropriate combination is chosen for the driving profile. The following chapters will attempt to identify a hybrid

drivetrain architecture that provides the optimal balance between improvements in fuel economy and the adverse effects on other mission performance parameters.

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III. CAPABILITY COMPARISION

A. INTRODUCTION

To identify a hybrid drivetrain architecture that provides the optimal balance between improvements in fuel economy and adverse effects on vehicle characteristics and mission performance parameters the capability of each hybrid system must be established. This chapter will compare the specific power, specific energy, energy conversion efficiency, cycle life, and specific cost for each of the hybrid drivetrain power sources and storage devices discussed in the previous chapter.

B. SPECIFIC POWER

Specific power is a measure of the power density of a power source. When comparing vehicle drivetrain power sources, specific power is often expressed as the power per unit weight (Watts per kilogram). Comparing the specific power of multiple power sources will provide an indication of their ability to accelerate a vehicle due to the speed at which they can deliver the power required. Table 1 lists the specific power of typical power sources used in a hybrid vehicle. The higher the specific power, the faster the vehicle will be capable of accelerating. A tactical vehicle would benefit from a power source with high specific power to enable it to ascend grades and quickly engage threats. The values in Table 1 and Figure 19 show that microturbines, flywheels, and ultracapacitors provide the greatest performance with regards to acceleration among the available power sources per kilogram of weight for the power source. Depending on the design of the ultracapacitor or flywheel, they are only able to deliver the high levels of power for up to three minutes before having to be recharged (Brecher, 2010). The diagonal lines in Figure 19 show the energy storage times (ratio of energy capacity to power) for each type of device. The microturbine is capable of continuously delivering the high levels of power when operated within the optimal speed range.

Table 1. Specific Power of Power Sources

	Primary Power Sources				Secondary Power Sources				
Power Source	Gasoline Engine (Truck)	Turbo-charged Diesel Engine (Truck)	Micro-turbine (Hydrogen)	Fuel Cell	Lead Acid Battery	Ni-MH Battery	Li-Ion Battery	Flywheel	Ultra-capacitor
Specific Power (W/kg)	400 [a]	286 [a]	2,000 [b]	300 [d]	240 [d]	200 - 300 [c]	260 - 420 [c]	600 - 5,600 [d]	3,305 [d]

[a] [After Heywood, 1988)]
[b] [After Jaguar, 2010)]
[c] [From Ehsani, Gao, & Emadi, 2010)]
[d] [From 21st Century Truck Program, 2000)]

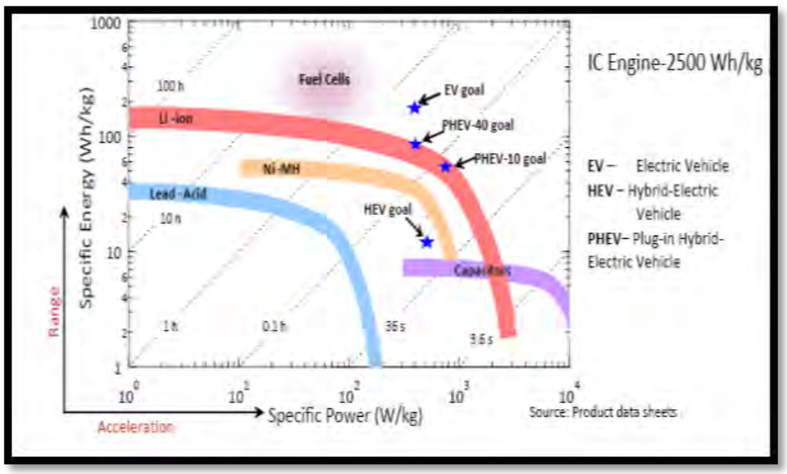

Figure 19. Relative Performance of Electrochemical Storage Devices. (From Brecher, 2010)

C. SPECIFIC ENERGY

Specific energy is a measure of the energy density of a power source. When comparing vehicle drivetrain power sources, specific energy is often expressed as the energy per unit weight (Watt hour per kilogram). Comparing the specific energy of multiple power sources will provide an indication of the operating range that a vehicle could travel. Table 2 lists the specific energy of typical power sources used in a hybrid vehicle. The higher the specific energy, the further the vehicle should be capable of

traveling. A tactical vehicle would benefit from a power source with high specific energy to enable it to increase its operating range and reduce the number of fuel trucks needed in convoys. The values in Table 2 Table 1. and Figure 19 show that the diesel engine offers the highest specific energy and theoretically the longest operating range per kilogram of weight for the power source. This is often the reason why most commercial vehicles are powered by diesel engines. Table 2 also shows a definite split in magnitudes of energy density between the primary power sources (combustion engines) and the secondary power sources (batteries, flywheels, and ultracapacitors) with the primary power sources being two to three times higher than the secondary power sources.

Table 2. Specific Energy of Power Sources

	Primary Power Sources				Secondary Power Sources				
Power Source	Gasoline Engine	Turbo-charged Diesel Engine	Micro-turbine (Hydrogen)	Fuel Cell	Lead Acid Battery	Ni-MH Battery	Li-Ion Battery	Flywheel	Ultra-capacitor
Specific Energy (Wh/kg)	305[a]	480[a]	333[a,b]	300[d]	35-50[c]	70-95[c]	80-150[c]	15-132[d]	2-5[c]

[a] [After Heywood, 1988)] Based on fuel prosperities and assuming a 25% energy efficiency for a gasoline engine, 40% for a diesel.
[b] [From Decuypere & Verstraete, 2004)] Assuming a 10% energy efficiency for a microturbine.
[c] [From Ehsani, Gao, & Emadi, 2010)]
[d] [From 21st Century Truck Program, 2000)]

D. ENERGY CONVERSION EFFICIENCY

The efficient conversion of energy from fuel into useable energy and the transmission of that energy through a drivetrain is an important factor when comparing hybrid drivetrain system architectures (combination of power sources and drivetrain components). The lower the efficiency of conversion and/or transmission of energy of the drivetrain system, the larger the power source will need to be to provide the same power required to propel the vehicle at a desired speed. Low energy efficiency in effect has three direct effects on the design of a vehicle: it increases the operating cost of the vehicle by increasing the fuel required, it lowers the operating envelope (speed and

range) of the vehicle, and it reduces the space available to carry cargo due to the increased space claim required for the power sources to meet the performance requirements of the vehicle.

The primary power sources range in efficiency from 10–48%, with the fuel cell providing the highest energy conversion efficiency (see Table 3). The secondary power sources range in efficiency from 70–95%, with the Li-Ion battery and the Ultracapacitor providing the highest energy conversion efficiency (see Table 3). Depending on the hybrid architecture (mild, series, or parallel) chosen for a vehicle, the energy generated from the power sources will need to be transmitted to the wheels either mechanically or electronically. Assuming negligible losses in the electric power cables, the electric drive motors provide the highest energy transmission efficiency (see Table 4). In terms of energy recovery systems, the integrated starter motor provides a greater percentage of recovered kinetic energy that is stored and returned to the wheels. Although the efficiency of an integrated starter motor is a function of the torque and speed of the unit, it is generally assumed to be approximately 80–85 percent when assisting the main engine in accelerating the vehicle (Jayabalan & Emadi, 2004).

Table 3. Energy Conversion Efficiency of Power Sources

	Primary Power Sources				**Secondary Power Sources**				
Power Source	Gasoline Engine	Turbo-charged Diesel Engine	Micro-turbine (Diesel)	Fuel Cell	Lead Acid Battery	Ni-MH Battery	Li-Ion Battery	Flywheel	Ultra-capacitor
Efficiency (%)	25-30 [e]	40-45 [e]	26[a]	48[b]	80 [e]	70 [e]	95 [e]	90[c]	95[d]

[a] [From Capstone Turbine Corporation, 2004)]
[b] [From 21st Century Truck Program, 2000)] At 25% of peak power
[c] [From Ruddell, 2003)]
[d] [From Cultura & Salameh, 2008)]
[e] [After 21st Century Truck Program, 2000)]

Table 4. Energy Conversion/Transmission Efficiency of Drivetrain Components

	Energy Transmission		Energy Recovery System	
Drivetrain Component	Electric Drive Motors	Transmission & Axle	Integrated starter motor	Regenerative Brake System
Efficiency (%)	92.5-94 [a]	90 [b]	80-85 [c]	60 [d]

[a] [From UQM, 2010)] Lower value under power delivery; higher value under power generation.
[b] [From Ehsani, Gao, & Emadi, 2010)]
[c] [From Jayabalan & Emadi, 2004)]. Efficiency experienced during acceleration support.
[d] [From 21st Century Truck Program, 2000)] Figure listed is for percentage of recovered kinetic energy that is stored and returned to the wheels approximately based on an urban driving cycle.

E. CYCLE LIFE

The logistical footprint generated by a vehicle system imposes a significant burden on the military services. Beyond having to transport the vehicles themselves and the fuel to power them, the military must also transport sufficient spare parts to keep them running. Every component has a useful life or lifespan at which point a significant deterioration of its performance takes place and requires replacement. This is known as the cycle life.

For the internal combustion engines listed in Table 5 the cycle life is based on the number of cold starts and ranges from the equivalent of 10 to 15 years of normal use. For the fuel cell, batteries, flywheel, and ultracapacitor the cycle life is based on the number of charge/discharge cycles. The cycle life for energy storage devices with low specific power (long discharge durations); such as the fuel cell and batteries; ranges from 500-6,500 cycles. Comparatively, the high specific power (short discharge duration) energy storage devices like the flywheel and ultracapacitor have cycles lives over one million. Therefore, when selecting the architecture for a hybrid vehicle there will need to be a trade-off between the duration that the power is delivered and the frequency at which the power source requires replacement.

Table 5. Cycle Life of Power Sources

	Primary Power Sources				Secondary Power Sources				
Power Source	Gasoline Engine	Turbo-charged Diesel Engine	Micro-turbine	Fuel Cell	Lead Acid Battery	Ni-MH Battery	Li-Ion Battery	Flywheel	Ultra-capacitor
Cycle Life (# of cycles)	16,425 [f]	16,425 [f]	10,000 [d]	10,950 [e]	500-1,000 [a]	750-1,200 [a]	1,000 [a]	>1,000,000 [b]	>1,000,000 [c]

[a] [From Ehsani, Gao, & Emadi, 2010)] Cycle life given for a full discharge cycle.
[b] [From Ruddell, 2003)]
[c] [From Miller, Prummer, & Schneuwly, 2009)]
[d] [From Capstone Turbine Corporation, 2003)]
[e] [From RTO Applied Vehicle Technology Panel (AVT), 2009)] Based on a life cycle of 5,000 hours (approximately 10 years of normal use), and use 3 times per day, 365 days per year.
[f] Based on a life cycle of approximately 15 years of normal use, 3 times per day, 365 days per year.

F. COST ANALYSIS

In an increasingly challenging fiscal environment, the Pentagon has been forced to take a hard look at the procurement and sustainment costs of new vehicle platforms. The rising unit costs and fuel consumption of vehicles are driving Program Managers to procure fewer vehicles and the military services to transport more fuel. To provide a viable solution, hybrid tactical vehicles must provide sufficient fuel economy gains to offset the additional cost of the hybrid drivetrain at a breakeven point within the useful life of the vehicle. The two main cost factors affecting the implementation of hybrid drivetrain architectures are the cost of the hybrid drivetrain components per unit energy output and the decrease in fuel consumption associated with their integration. The decreased fuel consumption can have significant positive impacts on the fully burdened cost of fuel (FBCF) depending on the method of delivery.

1. Energy Cost

The cost of hybridization of a vehicle can be determined from a comparison with similar systems or a component specific cost factor. Using the cost estimating method of reasoning by analogy it was determined that the hybrid version of a consumer vehicle was on average 15.4 percent more expensive than the same vehicle with a conventional drivetrain. The average hybrid price increase was calculated by evaluating conventional

and hybrid versions of vehicles from each vehicle category listed in Table 6. It can then be assumed by analogy that a hybrid version of a tactical vehicle such as a HMMWV would cost approximately 15.4 percent more than one containing a conventional drivetrain. The credibility of the analogous cost estimating figure is increased by the fact that the hybrid price increase for the vehicle category closest in size and configuration to a HMMWV (four wheel drive full size pickup) is nearly identical to the average. One thing to take into consideration with this cost estimate, however, is that each of the vehicles listed in Table 6 are only available with a parallel hybrid drivetrain. None of the vehicles incorporate a series hybrid drivetrain architecture. To date, none of the production series hybrid vehicles have a conventional drivetrain version. This is likely due to the difference in drivetrain layout between a series hybrid and a conventional drivetrain.

Table 6. Conventional vs. Hybrid Vehicle Costs (Base Price MSRP)

Vehicle Category	**Compact**	**Mid Size**	**Full Size**	**SUV**	**Full Size Pickup**
Vehicle	Honda Civic [a]	Nissan Altima [b]	Infiniti M [c]	Toyota Highlander [d]	Chevrolet Silverado [e]
Conventional Drivetrain ($)	20,505	21,840	47,050	36,110	39,010
Hybrid Drivetrain ($)	23,950	26,800	53,700	38,950	45,055
Hybrid Price Effect ($)	3,445	4,960	6,650	2,840	6,045
Hybrid Price Increase (%)	16.8	22.7	14.1	7.9	15.5

[a] [From American Honda Motor Co., Inc., 2011)] Based on a comparison between a 2012 Civic Sedan EX with an automatic transmission and a 2011 Civic Hybrid Sedan with a CVT.
[b] [From Nissan North America, Inc., 2011)] Based on a comparison between a 2011 Altima Sedan SL with a CVT and a 2011 Altima Sedan Hybrid with a CVT.
[c] [From Infiniti Worldwide, 2011)] Based on a comparison between a 2011 M37 RWD and a 2012 M35h RWD Hybrid.
[d] [From Toyota Motor Sales, U.S.A. Inc., 2011)] Based on a comparison between a 2011 Highlander 4WD SE and a 2011 Highlander Hybrid 4WD.
[e] [From (General Motors, 2011)] Based on a comparison between a 2011 Silverado 1500 2WD Crew Cab LTZ and a 2011 Silverado Hybrid 2WD Crew Cab 2HY.

At the component level power sources are compared using either the power specific cost ($/kW) or energy specific cost ($/kWh) factors (see Table 7). The component power specific costs range from $19–$1,100/kW for primary power sources, $12–$500/kW for secondary power sources and $10–$35/kW for drivetrain components

(Table 8). The high power specific costs of the microturbine and flywheel are due to their relative immature technology compared to the other power sources. The component energy specific costs range from $120–$16,000/kW for the secondary power sources. The very high energy specific cost of the ultracapacitor is due to its very low specific energy. There are no energy specific cost figures for components that convert or transfer energy, but do not store it. These components include the primary power sources, the integrated starter motor, and the electric drive motors. The regenerative braking system is not called out specifically as it encompasses the use of electric motors, energy storage devices, and control systems accounted for elsewhere in the hybrid system.

Table 7. Specific Cost of Power Sources

	Primary Power Sources				Secondary Power Sources				
Power Source	Gasoline Engine	Turbo-charged Diesel Engine	Micro-turbine	Fuel Cell	Lead Acid Battery	Ni-MH Battery	Li-Ion Battery	Flywheel	Ultra-capacitor
Power Specific Cost ($/kW)	19 [a]	28 [a]	750 - 1,100 [d]	19 - 48 [a]	80 [e]	75 [e]	75 [e]	200 – 500 [c]	12 [e]
Energy Specific Cost ($/kWh)	-	-	-	-	120 - 150 [b]	200 - 350 [b]	200 [b]	690–800 [c]	16,000 [e]

[a] [From Ogden, Williams, & Larson, 2004)]
[b] [From Ehsani, Gao, & Emadi, 2010)]
[c] [From Ruddell, 2003)] Cost range for steel rotor up to that for a composite rotor with a 5 second storage time.
[d] [From Capehart, 2010)]
[e] [From Miller, Prummer, & Schneuwly, 2009)]

Table 8. Specific Cost of Drivetrain Components

Drivetrain Component	**Integrated starter motor**	**Electric Drive Motors**
Power Specific Cost ($/kW)	25-35 [a]	10 - 20 [b]

[a] [From DeCicco, 2000)]
[b] [From Ogden, Williams, & Larson, 2004)].

2. Fully Burdened Cost of Fuel (FBCF)

In April 2007, the Defense Department's acquisition executive, Kenneth Krieg, signed a memo requiring the "fully burdened cost of fuel" be considered in the design trades for the Air Force's long-range strike concept, the Joint Light Tactical Vehicle (JLTV), and the Maritime Air and Missile Defense of Joint Forces alternative ship concepts (Krieg, 2007). This memo came after years of the Pentagon being unable to measure the actual cost of shipping fuel to its tactical vehicles deployed around the world. Depending upon the location and operational status of the tactical vehicle, fuel delivery costs range from $2.82–$600 per gallon (see Table 9).

Table 9. Fuel Cost by Delivery Method (From Erwin, 2010)

Delivery Method	Retail (Stateside)	Ground (Deployed–Peacetime)	Ground (Deployed–Hostile Area)	Helicopter (In theater)
Cost ($) / Gallon	2.82	13	100 - 600	400

The drive to improve fuel efficiency is to reduce the tremendous amount of fuel that the U.S. Military transports across the battlefield as well as reduce the size of convoys transporting the fuel. On average, 38.6% of the tonnage being transported to the front lines is fuel (Null, 2010). With the largest tactical wheeled vehicle fleet (246,000 vehicles, (21st Century Truck Program, 2000)) in the U.S. military, the Army consumes 44 million gallons of fuel per year during peacetime operations and 173 million gallons during wartime operations (Richard, 2010). For every 8,000 gallons that can be reduced, one fuel truck can be removed from a convoy (Siegel, 2008). Reducing convoy sizes improves tactical agility while reducing operational risks and anticipated combat casualties.

The next generation of tactical wheeled vehicles (the JLTV) is expected to travel on average each year approximately 12,179 miles per vehicle during wartime and peacetime operations; spend 2,828 hours idling; and consume 2,831 gallons of fuel assuming the same fuel consumption rate as a HMMWV (see Appendix B–Calculation of HMMWV Fuel Economy) (PM JLTV, 2011). Table 10 provides a breakdown of the

estimated dynamic and static operations expected to be conducted per vehicle during major combat, irregular warfare, and peacetime operations.

Table 10. Estimated Annual Fuel Consumption–JLTV (After PM JLTV, 2011)

	Mission Length (days)	Missions / Year	Miles/ Mission	Idle Hours/ Mission	Total Dynamic Operations (miles)	Total Static Operations (Idle-hours)	Est. Avg. mpg	Est. Avg. Gal/Hr	Total Fuel Used / year (gallons)
Major Combat Operations	3	27	236	50.6	6,369	1,366	11.3	0.62	1,410
Irregular Warfare Operations	7	17	253	86	4,310	1,462			1,288
Peacetime Operations	-	-	-	-	1,500	-			133
Total	-	44	-	-	12,179	2,828	-	-	2,831

What does this mean in a FBCF context? The capability of hybrid drivetrains to improve fuel economy of vehicles by up to 20% means an average annual savings per vehicle of 566 gallons (Table 11) and between $1,596 and $339,600 based on the fuel delivery method (Table 12). The 20% improvement across the 246,000 tactical wheeled vehicles (assuming equal fuel economy) translates to $0.39–$83.54 billion in annual savings for the Army alone (Table 12).

Table 11. Annual Fuel Savings per Vehicle–20% Improved Fuel Economy

	Fuel Used (gallons) / year	Annual Fuel Saved per Vehicle (gallons)
Major Combat Operations	1,410	282
Irregular Warfare Operations	1,288	258
Peacetime Operations	133	27
Total	2,831	566

Table 12. Annual Tactical Wheeled Vehicle Fleet Fuel Savings–20% Improved Fuel Economy

Delivery Method	Retail (Stateside)	Ground (Deployed–Peacetime)	Ground (Deployed–Hostile Area)	Helicopter (In theater)
Cost ($) / Gallon [a]	2.82	13	100–600	400
Gallons Saved / Vehicle / Year	566			
Savings ($) / Vehicle	1,596	7,358	56,600–339,600	226,400
Tactical Wheel Vehicles	246,000			
Total Annual Savings ($billion)	0.393	1.81	13.92–83.54	55.69

[a] Fuel cost data from Table 9.

G. CHAPTER SUMMARY

The hybrid drivetrain architecture for a vehicle that provides the optimal balance between improvements in fuel economy and adverse effects on vehicle characteristics and mission performance parameters can vary depending on the anticipated use of the vehicle. A vehicle that will spend the majority of the time at constant speeds will benefit the most from a power source with high specific energy while a vehicle that conducts a large amount of stop and go movements will benefit the most from a power source with high specific power. Overall energy conversion and transmission efficiency will reduce operational costs and component sizes. High cycle lives will reduce the need for component redundancy and shrink the logistical footprint of the vehicle. Over time, improvements in technology will increase energy densities and the technology maturity of hybrid power sources and components which in turn will lower specific costs factors. In the end, the breakeven point for developing a hybrid tactical vehicle that is cost-effective will depend on the type and location of use.

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IV. IMPACT ANALYSIS

A. INTRODUCTION

The selection of a hybrid drivetrain for a tactical vehicle needs to take several performance factors and vehicle attributes into consideration as well as the intended use of the vehicle. An understanding of all of these aspects of vehicle design is imperative to selecting the optimal hybrid drivetrain architecture for the desired characteristics of the vehicle. This chapter will evaluate the impact of various hybrid drivetrain architectures on the aspects of vehicle layout, mobility, transportability, safety, and survivability. The impact analysis in this chapter will focus on evaluating general hybrid drivetrain architectures and their effects of integration on a tactical vehicle. The general hybrid drivetrain architectures that will considered in this analysis will be a mild, parallel, and a series hybrid. Unless specified otherwise, all comparisons made will be considered to apply to all variations of the three general architectures.

B. VEHICLE LAYOUT

Within the volumetric space of a vehicle design, the drivetrain, crew, and cargo compartments define the entire envelope of available space. This design envelope imposes an inverse relationship between the compartments in which a change in the volume (number of components) or configuration (design flexibility) of one compartment will affect one or more of the other compartments. The extent of the impact is largely dependent on the type of hybrid drivetrain.

Compared to a conventional drivetrain a mild hybrid (see Figure 12) has a net increase of one component (motor controller) and a negligible increase in net volume. There is often no difference in size between the integrated starter/generator and the torque converter that it replaces in a mild hybrid. The motor controller can also be integrated with the existing drivetrain controller to minimize the space claim. And there is no change in the size of the internal combustion engine in a mild hybrid. In terms of drivetrain configuration, the mild hybrid does not provide any increase or reduction in packaging flexibility.

A parallel hybrid has a net increase of three components (inverter/converter, motor controller, and a high voltage energy storage device) and a moderate increase in net volume. The integrated starter/generator again replaces the torque converter, as in the mild hybrid. The addition of power from the electric motor is often sufficient enough to allow a reduction in the size of the internal combustion engine of up to 25% (RTO Applied Vehicle Technology Panel (AVT), 2009). Many of the commercial parallel hybrids in production today supply the same combined power levels of a six cylinder with the use of a four cylinder and an electric motor. The addition of the high voltage energy storage device, however, generally reduces the size of the cargo compartment. Overall, the drivetrain configuration of a parallel hybrid is more complex than a conventional drivetrain and results in a reduction in packaging flexibility.

A series hybrid has a zero to net decrease of one component and a moderate decrease in net volume. The addition of a generator, inverter/converter, motor controller, a large high voltage energy storage device, and 2–4 traction motors are offset by the elimination of the torque converter, transmission, transfer case, driveshafts, possibly all halfshafts, and possibly both differentials. The variation in the number of traction motors, halfshafts, and differentials is dependent on whether the differentials in the four wheel drive system are integrated with the traction motors or eliminated entirely by using four in-wheel hub motors. Since the internal combustion engine in a series hybrid only charges the energy storage device and is designed to run within its optimal operating range, it can be reduced in size by up to 50% (RTO Applied Vehicle Technology Panel (AVT), 2004). For example, the High Power Density (HPD) diesel engine developed for tanks by German manufacturer MTU (Figure 20), not only decreases the volume of the engine by 50% compared to the MTU 883 conventional drivetrain (Figure 21), but also the weight (RTO Applied Vehicle Technology Panel (AVT), 2004). Figure 22 provides a direct cross-sectional size comparison of the two MTU engines. Overall, the drivetrain configuration of a series hybrid is less complicated than a conventional drivetrain and results in an increase in packaging flexibility as the high voltage power cables are not restricted to rigid connections between components.

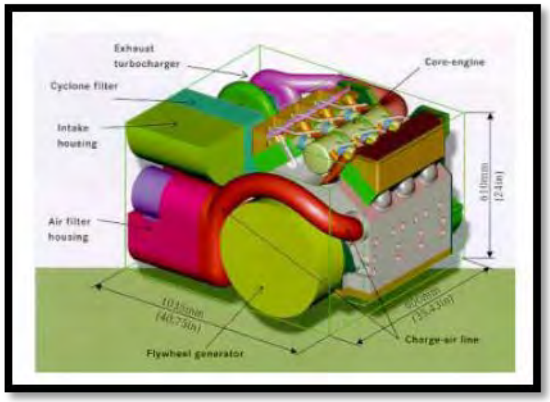

Figure 20. HPD Engine Packaging. (From RTO Applied Vehicle Technology Panel [AVT], 2004)

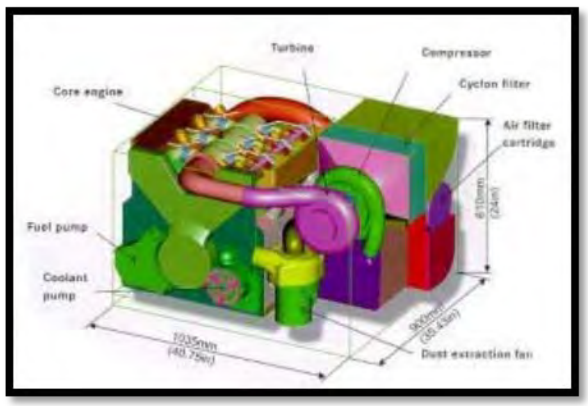

Figure 21. MTU 883 Engine Packaging.
(From RTO Applied Vehicle Technology Panel [AVT], 2004)

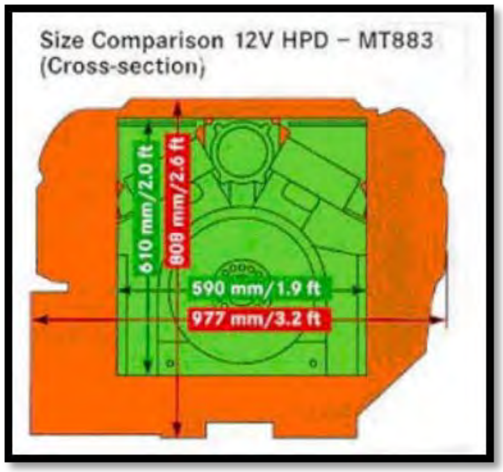

Figure 22. MTU 883 vs. HPD Engine Size Comparison.
(From RTO Applied Vehicle Technology Panel [AVT], 2004)

C. MOBILITY

Vehicle mobility is composed of several aspects of maneuverability and performance. This section will identify the impacts of mild, parallel, and series hybrid architectures on tractive effort, handling, steering, acceleration, braking, and longitudinal grade capabilities.

1. Maneuverability

The tractive effort is mildly improved over a conventional drivetrain in mild and parallel hybrid architectures due to the torque added by the electric motor. Tractive effort is further improved when a series hybrid architecture is used. When traveling above 9 mph a two traction motor series hybrid performed better than the conventional drivetrain, but performed significantly less than 9 mph (RTO Applied Vehicle Technology Panel (AVT), 2004). Increasing the number of traction motors from two to four in a series hybrid can increase the maximum tractive effort capability up to an additional 10 percent (RTO Applied Vehicle Technology Panel (AVT), 2004). Overall, a four traction motor series hybrid performs much better than a conventional drivetrain throughout the speed range.

The overall handling characteristics of a vehicle are improved by all three hybrid architectures. The reduction in size of the internal combustion engine and the placement

of the energy storage devices low in the vehicle, lowers the center of gravity and reduces body roll. The use of wheel hub motors in a series hybrid enables precise traction control of each wheel by implementing a technique known as torque vectoring (Dalsjo, 2008). Torque vectoring is the application of power to any wheel that has traction nearly instantly without having to use brakes or cut power to wheels that are slipping. The result of torque vectoring is that the vehicle can maintain higher speeds during corning maneuvers and rapid changes in direction by transferring more power to the outside wheels (see Figure 23). While it is possible to implement torque vectoring capabilities into a conventional drivetrain or a mild or parallel hybrid, the architecture of a wheel hub series hybrid simplifies the integration and implementation of the capability.

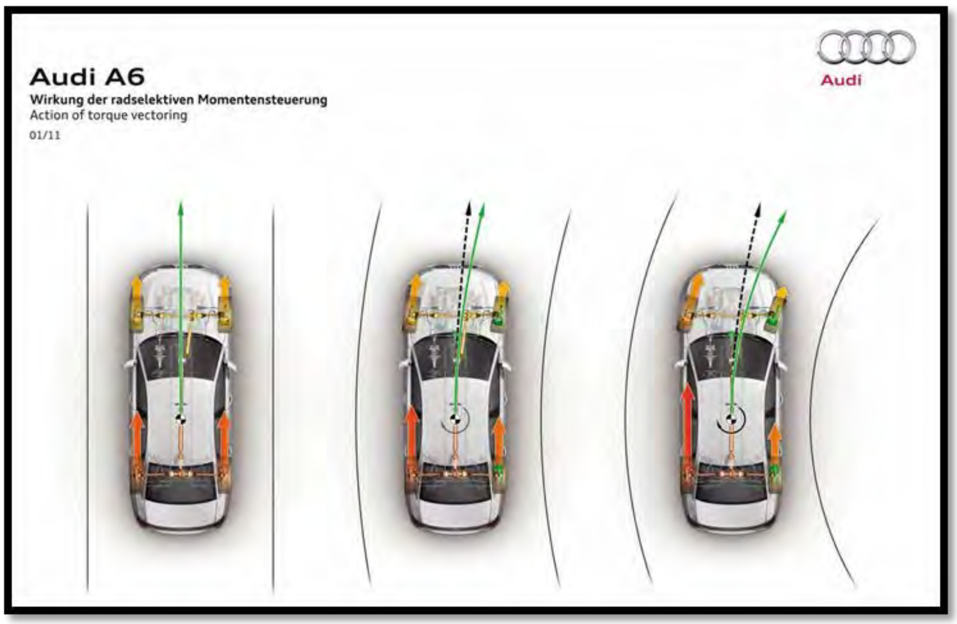

Figure 23. Torque Vectoring Application of Power Through a Turn. (From Audi, 2011)

The steering capability of a vehicle is not impacted by the integration of a mild or parallel hybrid. A wheel hub motor series hybrid again provides increased maneuverability due to the capability to perform dual steering (RTO Applied Vehicle Technology Panel (AVT), 2004). Dual steering is the combination of the natural steering angle and skid steering.

2. Performance

The acceleration capability of all three hybrid architectures is better than conventional drivetrains at speeds approaching 60 mph. As speeds rise above 60 mph, the conventional drivetrain begins to accelerate faster than the hybrid drivetrains. This is due to higher speeds requiring significantly more horsepower to overcome aerodynamic drag. Hybrid drivetrains utilizing peak power secondary power sources (flywheel or ultracapacitor) have shown improvements in acceleration performance of 20–36 percent over conventional drivetrains (RTO Applied Vehicle Technology Panel (AVT), 2004). Since tactical vehicles rarely travel at speeds above 60 mph, the hybrid drivetrains lack of performance improvement above that speed is inconsequential. In terms of braking performance the hybrid architectures impart no discernable difference unless using a series hybrid with wheel hub motors, in which case the braking distances will likely be longer if the braking system in not enhanced due to the increased rotational inertia from the wheel hub motors.

The longitudinal grade performance (also known as "gradeability") is another variable that is drivetrain configuration dependent. On longitudinal grades above 20 percent, series hybrids with differential integrated traction motors exhibit higher sustained speeds compared to a conventional drivetrain (RTO Applied Vehicle Technology Panel (AVT), 2004). When the number of tractor motors in increased to four as in the wheel hub architecture, the series hybrid out performs the conventional drivetrain throughout the range of grades. One issue that arises when using a series hybrid on a longitudinal grade is that the service brake and the throttle cannot be used simultaneously to insure a smooth transition to ascend the respective grade. The traction motors are not capable of operation in both scenarios at the same time. The simultaneous application of brake and throttle would not be an issue with a mild or parallel hybrid as both of those architectures retain conventional friction brakes.

In reviewing the mobility impacts of a hybrid drivetrain it is readily apparent that the effects are not only dependent on the type of hybrid, but also the configuration of that particular type of hybrid. A parallel hybrid design with "power boosting" in mind will behave and perform differently than one designed for "efficiency." A series hybrid with

traction motors integrated into the differentials will behave and perform differently than one designed with wheel hub motors. In this vein, the type and configuration of hybrid needs to be selected for the desired driving characteristics.

D. TRANSPORTABILITY

There are three modes of transport that a hybrid vehicle must be capable of in a military environment; land, sea, and air. Each environment imposes significantly different challenges to the integration of a tactical vehicle. The transport of a tactical vehicle across land, whether by truck or rail, does not impose any unique impacts on a hybrid vehicle. Sea transportation, amphibious use, and fording raise issues concerned with the interaction of water, possibly salt, with high voltage components and battery chemistries. This does not impose any limitations on hybrid vehicles; rather, it imparts increased consideration of waterproofing. The large variations in altitude encountered during air transport can cause issues for several different hybrid architectures utilizing pressurized containers or batteries. While this issue will not preclude the hybrid vehicle from being air transported, it will require additional design elements or preparation steps before being loaded on the aircraft. One such additional preparation step would be to release some of the pressure from the pressurized container.

E. SAFETY

Each hybrid architecture introduces unique safety precautions that are not present in a conventional vehicle. For the majority of hybrid architectures with electrically based energy storage devices, there is an increased risk of electrical shock due to the high operational voltages. The presence of high voltage cables will require design elements to isolate the high voltages in the event of a crash or damage from a threat interaction. The design elements can include emergency disconnects, access door power interlocks, and careful consideration of cable routing (21st Century Truck Program, 2000). The technicians that maintain hybrids with electrically based energy storage devices require specialized training to deal with the high voltages. This risk can be mitigated by discharging the stored energy before maintenance, as is done on the Oshkosh Truck HEMTT A3 (Oshkosh Truck Corporation, 2003). By doing so, the vehicle will not

require specially trained technicians. The safety of the stowed ammunition must also be considered in the design of a hybrid tactical vehicle. The high current and voltages that electrically based hybrid vehicles operate at have the potential to introduce electromagnetic fields which may influence electrical fuses and igniters (RTO Applied Vehicle Technology Panel (AVT), 2009). The effects of magnetic fields are comparatively lower in a conventional vehicle since they operate on low voltage electrical systems.

Mechanical hybrids utilizing flywheel energy storage devices must contend with containment issues similar to conventional internal combustion engines. In the event of an internal component failure, the fragments must not enter the crew compartment. The internal combustion engine accomplishes this by catching dislodged pistons and connecting rods within the engine block and cylinder heads. In the event of damage to a flywheel, the stored energy will be released within seconds. The corresponding power released can be on the order of 720–3,600 kW, based on a 1-kWh flywheel (Ehsani, Gao, & Emadi, 2010). Therefore, containment of the released energy and rotor fragments is paramount. One approach to mitigate the risk is to increase the thickness of the rim of the rotor, effectively creating a mechanical fuse that will break first at the instant the rotor suffers from a failure. By implementing the mechanical fuse design into the steel rotor, only the mechanical energy stored in the rim needs to be dissipated in the casing upon failure (Ehsani, Gao, & Emadi, 2010). When a composite rotor is used, the released energy is comparatively much lower as the composite rotors delaminate rather than break apart in large fragments upon failure. Mechanical hybrids utilizing high pressure vessels present an increased risk of vehicle damage or injury compared to conventional vehicles if the tanks are not sufficiently restrained. Damage to a high pressure tank will not cause it to rupture, but the release of the high pressure fluid could propel the tank with sufficient force to cause damage or injury. The presence of this risk is why technicians should be trained to release the pressure before working on the container.

In general, the safety of a hybrid vehicle is not dependent on the drivetrain architecture (mild, parallel, or series), but on the components selected for each architecture. Each of the drivetrain architectures can be developed using electrically or

mechanically based energy storage and transmission devices. Therefore, the overall safety impact is solution specific and will be an aggregate of the components chosen.

F. SURVIVABILITY

The subject of survivability of a tactical vehicle includes considerations of vehicle signatures, threat protection, and vulnerability. The hostile environment in which tactical vehicles operate and the increased use of irregular warfare has made survivability a top priority for military commanders. The impacts of hybrid drivetrains on survivability will be discussed in this section.

1. Vehicle Signatures

A tactical vehicle is identified by adversaries by visual, infrared, acoustic, and magnetic signatures. The visual signature of a vehicle is simply the unique size, shape, and location of exterior components that would allow an adversary to identify the vehicle. The visual signature of a vehicle is not impacted by the integration of a mild, parallel, or a series hybrid with differential integrated traction motors. The configuration of wheel hub motor series hybrids enables the use of trailing arm suspensions which require less space than a double wishbone suspension typically used with other drivetrain architectures (Dalsjo, 2008). This results in a larger available volume inside the vehicle and a lower vehicle height/silhouette (see Figure 24). The added capability to fold and reduce the height of the suspension enables the vehicle to be transported in smaller aircraft.

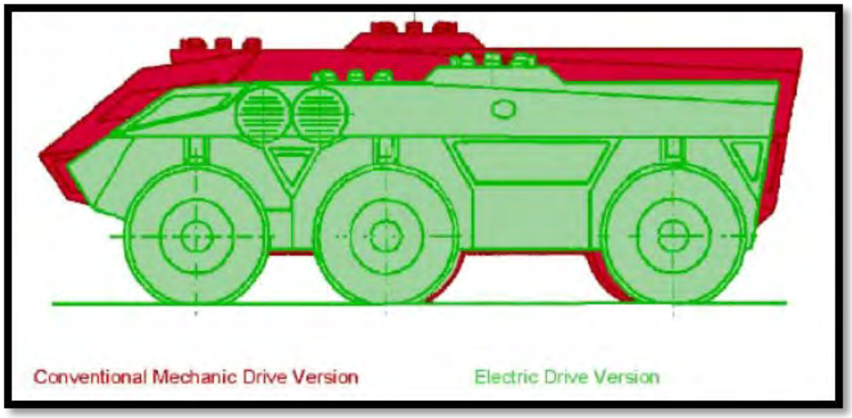

Figure 24. Reduction of Vehicle Silhouette by use of Electric In-Hub Drives. (From RTO Applied Vehicle Technology Panel [AVT], 2004)

The infrared signature of a vehicle is based on the size and location of the heat sources. The larger the infrared (heat) signature is for a vehicle, the easier it is to detect. Conventional drivetrain vehicles emit large amounts of heat from the engine, exhaust, and brakes. The use of regenerative brakes in all three general hybrid architectures reduces the work that friction brakes must perform, thereby reducing the heat they generate and lowering the infrared signature. (21st Century Truck Program, 2000). The use of parallel or series hybrids reduces the infrared signature even further by reducing the size of the internal combustion engine. The traction batteries or fuel cells used in parallel and series hybrids do not adversely affect the infrared signature as they generate much less heat than an internal combustion engine.

The acoustic signature of a vehicle consists of the unique sounds and sound levels that are emitted during operation. The acoustic signature of a vehicle is not impacted by the integration of a mild hybrid drivetrain architecture. The use of parallel or series hybrids reduces the acoustic signature by reducing the size of the internal combustion engine and consequently lowering the sounds levels emitted through the exhaust.

The magnetic signature of a vehicle consists of the local disturbance of the earth's magnetic field caused by the presence of magnetic fields generated by ferromagnetic materials and electronic devices. Electrically based hybrid vehicles have the potential for larger magnetic signatures due to the increased presence of local magnetic fields if they

do not integrate proper shielding measures (RTO Applied Vehicle Technology Panel (AVT), 2009). Mechanically based hybrid vehicles have magnetic signatures comparable to conventional vehicles.

2. Threat Protection

Active protection systems and electronic and magnetic weapons in development and in use in the future will increase the desire for pulse power supplies. The ability of any of the three general architectures to integrate ultracapacitors and flywheels allows them to generate the high power levels and short delivery durations needed to improve the capability in this area. Figure 25 depicts the estimated pulse power requirements needed for future active protection systems, active armor, and electronic and magnetic weapons.

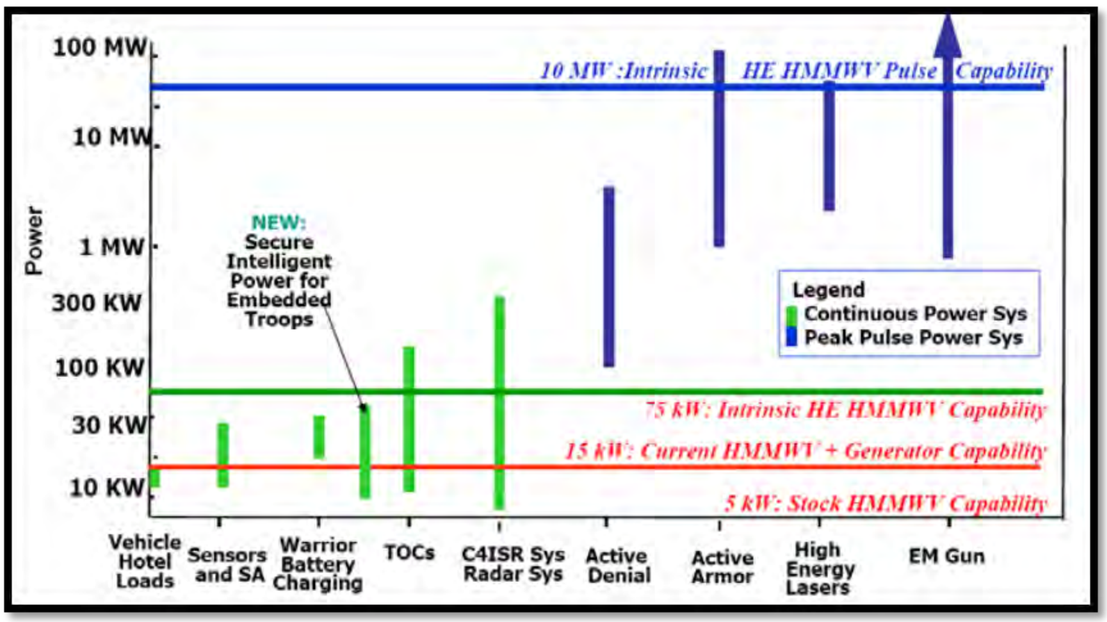

Figure 25. Estimated Power Requirements for Integrated Systems for the Next and Future Generations of Military Vehicle. (From Dalsjo, 2008)

3. Vehicle Vulnerability

The vulnerability of a vehicle is the ease with which an adversary can disable a major vehicle system or the vehicle entirely. Vulnerability can be reduced by providing protection around critical systems, reducing or eliminating cascading failures, and

eliminating single point failures. Mild and parallel hybrids provide a mild decrease in vulnerability compared to a conventional drivetrain by allowing the secondary power source and the integrated starter generator to limp the vehicle out of a dangerous area for a short distance. Series hybrids provide a moderate decrease in vulnerability by providing a greater limp capability due to the larger secondary power source and the ability to continue moving even after power has been lost to one of the axles. This is possible because the series hybrid powers each axle or wheel individually.

Hybrid drivetrain architectures provide unique opportunities to improve survivability in tactical vehicles in the area of signatures, threat protection, and vulnerability. The degree to which the survivability is improved is dependent on the hybrid architecture. However, electrically based hybrids have the potentially to decrease survivability with respect to magnetic signatures if shielding measures are not effectively integrated.

G. CHAPTER SUMMARY

The impact generated by the integration of hybrid drivetrains in tactical vehicles is dependent on the general hybrid drivetrain architecture for some aspects and the type of energy source (electrical or mechanical) for others. In general the series hybrid architecture provides the greatest improvement over a conventional vehicle in the areas of mobility and survivability, while having the smallest negative impact on vehicle layout. The transportation, safety, and magnetic signature of a vehicle are negatively impacted by electrically based and to a lesser degree, mechanically based hybrid architectures. The negative impact is a result of increased risks and additional steps required to equal the capability of a conventional drivetrain. Therefore, based on the findings in this chapter, a mechanically based series hybrid would provide the greatest improvement in performance with the smallest negative impact.

V. CONCEPT SELECTION

A. INTRODUCTION

The design of a hybrid drivetrain architecture for tactical vehicles requires a method for choosing between the available alternatives. The decision evaluation theory chosen is dependent on the type, complexity, and availability of information. The theory chosen must consider that selection criteria could be either quantitative or qualitative in nature. This chapter will apply decision evaluation methods to determine the optimal hybrid drivetrain architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements.

B. CONCEPT SCORING

The selection criteria used to support the decision evaluation are the operating range, power to weight ratio, efficiency, cycle life, cost (power and energy), transportability, safety, logistical footprint, mobility, and survivability of the various hybrid drivetrain concepts. The large number of selection criteria necessitated the use of a multiple criterion decision theory. The theory chosen to evaluate the hybrid drivetrain architectures was an additive weighting method of evaluation with scaling. The ratings of the quantitative criteria are based on a scaling equation to correspond to a one to five rating scale, with five being the most desirable. The scaling equation is different for each quantitative selection criteria as they each have different ranges of values. The rating of the qualitative criteria is based on comparing alternatives against a standard or reference concept. The qualitative rating scale is given in Table 13.

Table 13. Qualitative Selection Criteria Rating Scale

Moderate Degradation	Mild Degradation	Same as Reference	Mild Improvement	Moderate Improvement
1	2	3	4	5

The importance and/or priority of each selection criteria were determined by surveying a Systems Engineer for capability development at the Combat Development and Integration (CD&I) Division within the Marine Corps Combat Development Command (MCCDC). The particular Systems Engineer that was surveyed was chosen based on the fact that they worked as a requirements officer for tactical ground vehicles. As such, their duties include representing the warfighter's needs and advocating for the end use customer, the Marine in the field. The weights assigned to each criteria are listed in the "Tactical Ground Vehicle–Attribute Weighting Survey" in Appendix A.

1. Quantitative Selection Criteria

a. Specific Power

The specific power of the primary and secondary power source concepts examined in this paper ranged from 240–5,600 W/kg. The scaling equation was derived by using the equation of a trendline connecting the minimum and maximum limits for the independent and dependent variables based on a logarithmic scale. The specific power criteria scoring equation is listed below.

$$\text{Score} = 0.4343 * \ln(\text{Specific Power}) \qquad \text{(Equation 5-1)}$$

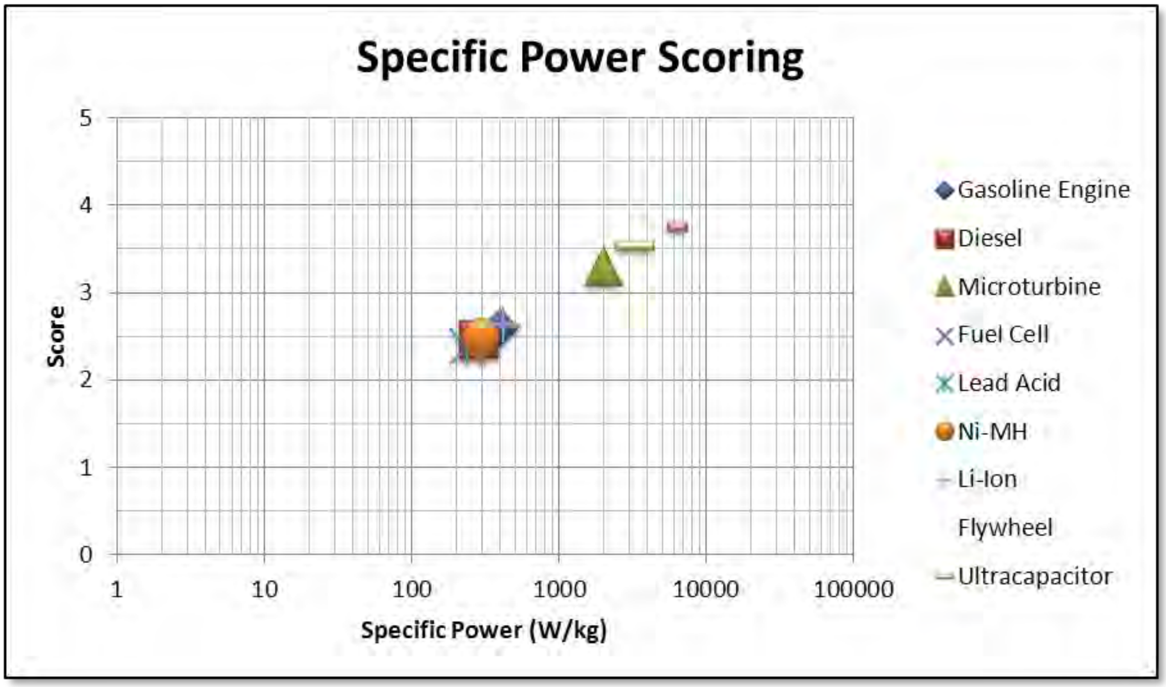

Figure 26. Specific Power Scoring

b. Specific Energy

The specific energy of the primary and secondary power source concepts examined in this paper ranged from 5–480 Wh/kg. The scaling equation was derived by dividing the specific energy by 100. The specific energy criteria scoring equation is listed below.

$$\text{Score} = (\text{Specific Energy}) / 100 \qquad \text{(Equation 5-2)}$$

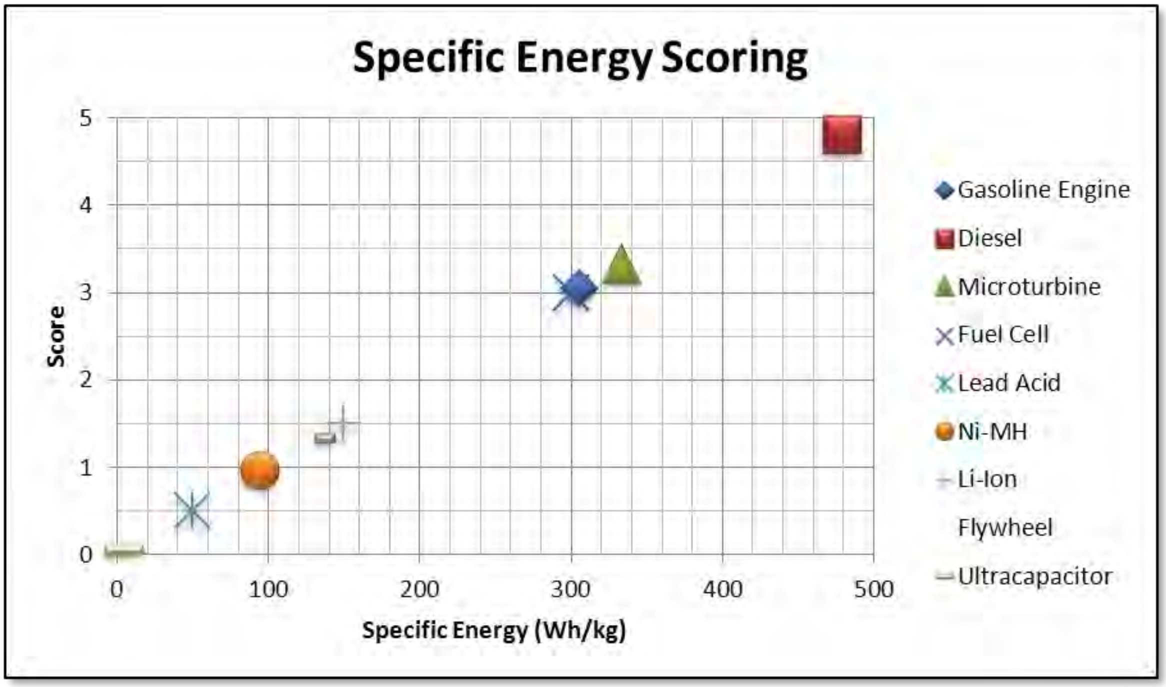

Figure 27. Specific Energy Scoring

c. Efficiency

The efficiency of the primary and secondary power source concepts examined in this paper ranged from 25–95 percent. The scaling equation was derived by dividing the percent efficiency by 20. The efficiency criteria scoring equation is listed below.

$$\text{Score} = (\text{Percent Efficiency}) / 20 \qquad \text{(Equation 5-3)}$$

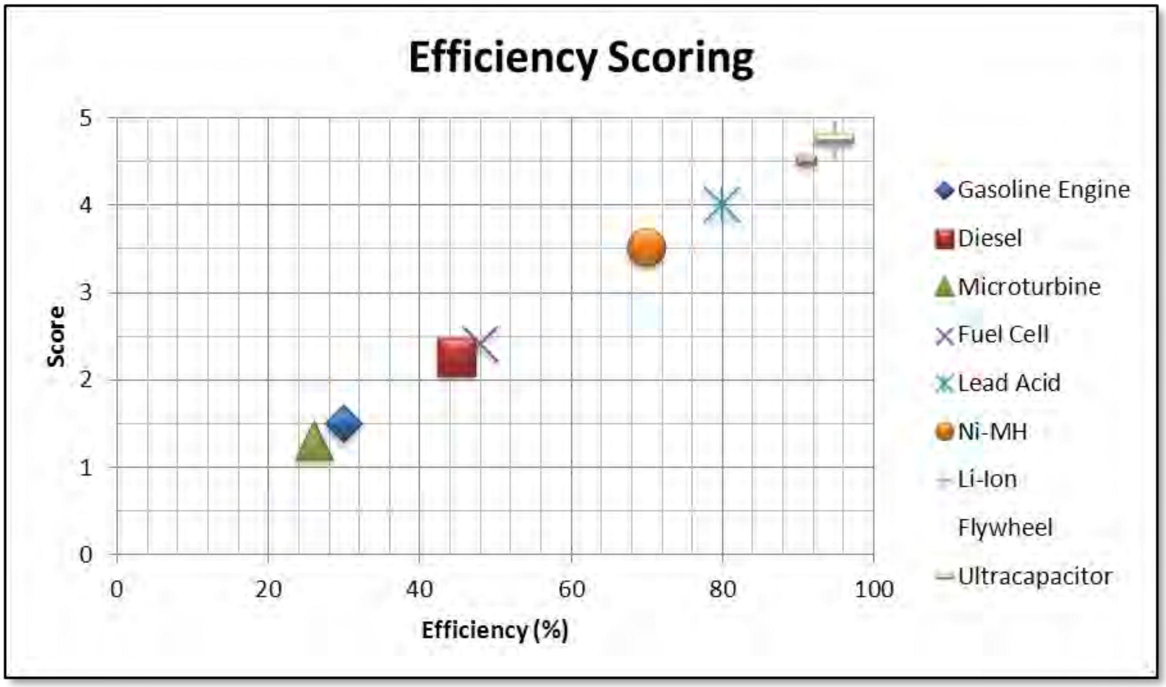

Figure 28. Efficiency Scoring

d. Cycle Life

The cycle life of the primary and secondary power source concepts examined in this paper ranged from 100–1,000,000 cycles. The scaling equation was derived by using the equation of a trendline connecting the minimum and maximum limits for the independent and dependent variables based on a logarithmic scale. The cycle life criteria scoring equation is listed below.

$$\text{Score} = 0.4343*\ln(\text{\# of Cycles / Life})–1 \qquad \text{(Equation 5-4)}$$

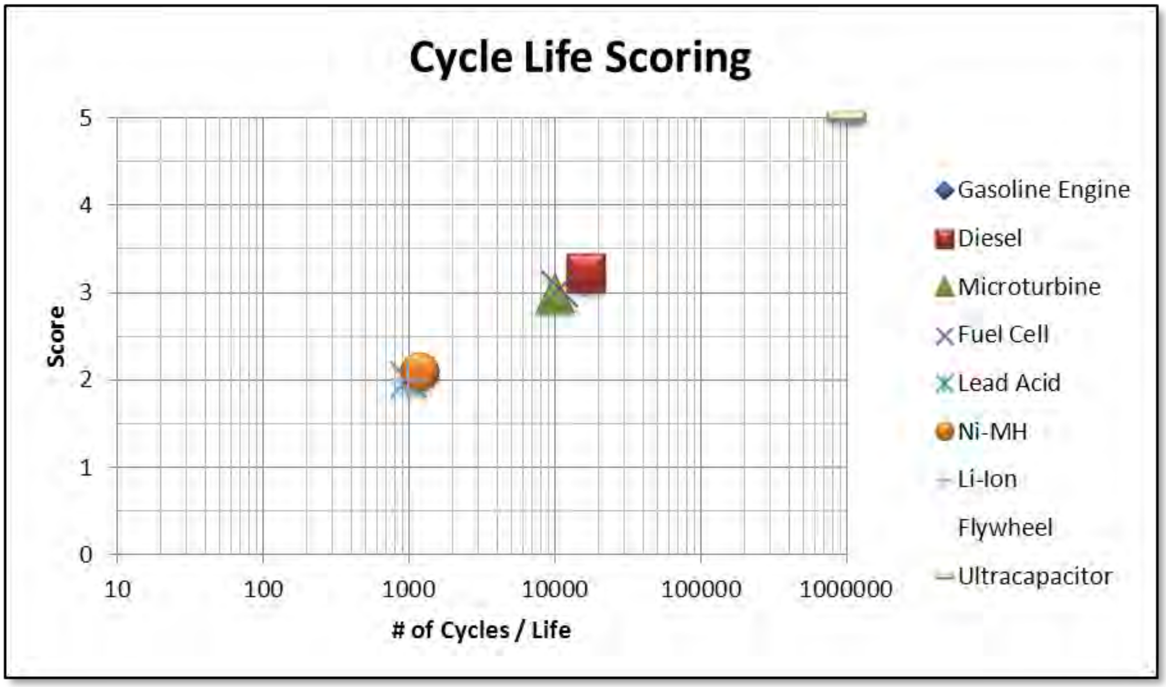

Figure 29. Cycle Life Scoring

e. Power Specific Cost

The power specific cost of the primary and secondary power source concepts examined in this paper ranged from \$12–\$750 per kilowatt. The scaling equation was derived by penalizing the concept as the cost approached the upper limit of \$1,000 per kilowatt. The power specific cost scores were based on the best case scenario attribute values (lowest cost per kilowatt). The power specific cost criteria scoring equation is listed below.

$$\text{Score} = ((1000-(\text{Power Specific Cost})) / 1000) * 5 \qquad \text{(Equation 5-5)}$$

Figure 30. Power Specific Cost Scoring

f. Energy Specific Cost

The energy specific cost of the primary and secondary power source concepts examined in this paper ranged from $120–$16,000 per kilowatt-hour. The scaling equation was derived by penalizing the concept as the cost approached the upper limit of $100,000 per kilowatt-hour based on a logarithmic scale. The energy specific cost scores were based on the best case scenario attribute values (lowest cost per kilowatt-hour). The energy specific cost criteria scoring equation is listed below.

$$\text{Score} = 5 - 0.4343 * \ln(\text{Energy Specific Cost}) \qquad \text{(Equation 5-6)}$$

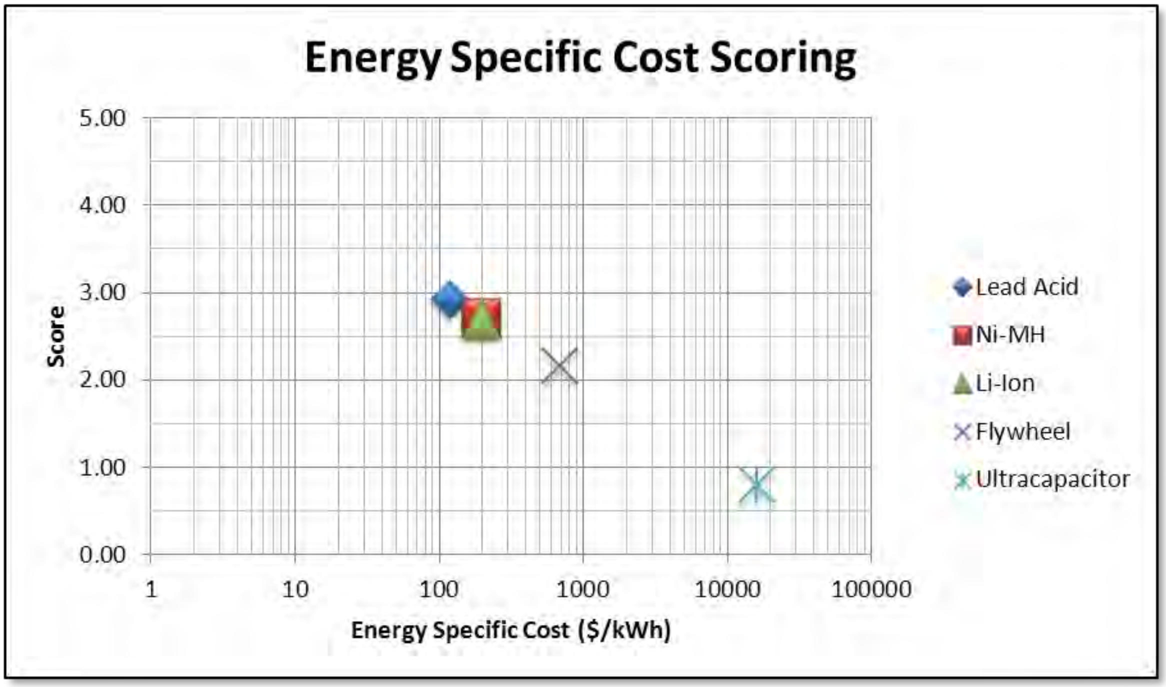

Figure 31. Energy Specific Cost Scoring

2. Qualitative Selection Criteria

The qualitative selection criteria for hybrid drivetrain architectures include transportability, safety, logistical footprint, mobility and survivability. The weighted rating scores for these criteria were determined using the rating scale in Table 13 and the attribute weights provided in the survey from Appendix A. In the event that a selection criterion was broken down into sub-criteria, the parent criteria weighting was distributed evenly across the sub-criteria. For the transportability and safety criteria, the variance in performance was largely due to the state in which the energy was stored. Therefore, these elements were rated on how an electrically or mechanically based hybrid compared to a chemical energy (fuel) based conventional drivetrain (see Table 14). The mechanical energy based hybrid provided the best performance compared to a conventional drivetrain, but did not equal or outperform it all areas. While the mechanical hybrid exhibited degraded performance in air transportation and specialized training due to the

presence of high pressure vessels in some designs, these risk areas could be mitigated with design solutions which would bring the capability back to equal with the conventional drivetrain.

Table 14. Energy State Scoring Matrix

		Fuel Energy Based (Reference)		Electric Energy Based		Mechanical Energy Based	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Transportability	10%						
Land Transport	3.33%	3.00	0.10	3.00	0.10	3.00	0.10
Sea Transport	3.33%	3.00	0.10	2.00	0.07	3.00	0.10
Air Transport	3.33%	3.00	0.10	2.00	0.07	2.00	0.07
Safety	10%						
Electrical Shock	2.50%	3.00	0.08	2.00	0.05	3.00	0.08
Special Training	2.50%	3.00	0.08	2.00	0.05	2.00	0.05
Stowed Ammo	2.50%	3.00	0.08	2.00	0.05	3.00	0.08
Containment	2.50%	3.00	0.08	2.00	0.05	3.00	0.08
	Net Score	0.53		0.38		0.47	
	Rank	1st		3rd		2nd	

The variance in performance for the logistical footprint, mobility, and survivability criteria was largely dependent on the type of general hybrid architecture. These criterion were, therefore, rated on how a series, parallel, or mild hybrid compared to a conventional drivetrain (see Table 15). The series hybrid provided the best performance compared to a conventional drivetrain, greatly outperforming it in the areas of tractive effort and reducing vulnerability.

Table 15. General Hybrid Architecture Scoring Matrix

		Conventional Drivetrain (Reference)		Series Hybrid		Parallel Hybrid		Mild Hybrid	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Logistical Footprint / Complexity (# of components)	5%	3.00	0.15	2.00	0.1	1.00	0.05	2.00	0.10
Mobility	10%								
Tractive Effort	1.67%	3.00	0.05	5.00	0.08	4.00	0.07	4.00	0.07
Handling	1.67%	3.00	0.05	4.00	0.07	4.00	0.07	4.00	0.07
Steering	1.67%	3.00	0.05	4.00	0.07	3.00	0.05	3.00	0.05
Acceleration	1.67%	3.00	0.05	4.00	0.07	4.00	0.07	4.00	0.07
Braking	1.67%	3.00	0.05	2.00	0.03	3.00	0.05	3.00	0.05
Longitudinal Grade	1.67%	3.00	0.05	4.00	0.07	3.00	0.05	4.00	0.07
Survivability	5%								
Visual Signature	0.83%	3.00	0.03	4.00	0.03	3.00	0.03	3.00	0.03
Infrared Signature	0.83%	3.00	0.03	4.00	0.03	4.00	0.03	3.00	0.03
Acoustic Signature	0.83%	3.00	0.03	4.00	0.03	4.00	0.03	3.00	0.03
Magnetic Signature	0.83%	3.00	0.03	2.00	0.02	3.00	0.03	3.00	0.03
Threat Protection	0.83%	3.00	0.03	4.00	0.03	4.00	0.03	4.00	0.03
Vulnerability	0.83%	3.00	0.03	5.00	0.04	4.00	0.03	4.00	0.03
	Net Score	0.60		0.68		0.58		0.63	
	Rank	3rd		1st		4th		2nd	

Each of the general hybrid architectures listed in Table 15 will require a traction motor to be integrated into the drivetrain. There are six different types of traction motors available on the market. They consist of the asynchronous motor (ASM), permanent magnet motor (PM), switched reluctance motor (SRM), direct current motor (DCM) and the synchronous motor (SYM) (RTO Applied Vehicle Technology Panel (AVT), 2004). Based on the selection criteria specifically applicable to traction motors listed in Table 16, the permanent magnet motor provides the best overall performance, excelling in areas of size per weight, speed, efficiency, and controllability.

Table 16. Comparison of Traction Motor Types. (From RTO Applied Vehicle Technology Panel [AVT], 2004)

(0 Is Neutral, + Means Better, – Means Less Good)

	ASM	PM	SRM	DCM	SYM
Motor Size Mass	0	+	0	–	0
High Speed	+	+	+	–	–
Endurance Maintenance	+	0	+	–	–
Efficiency	0	+	0	–	0
Controller Size Mass	0	0	0	+	0
Controllability	+	+	–	+	0
Number Power Devices	0	0	+	+	0
Reliability	0	0	0	0	0
TOTAL	+++	++++	++	– –	– –

3. Power Source Scoring Matrices

The scoring for the primary power sources was determined by combining the scores of the quantitative criteria from Section 5.B.1. and the scores from Table 14 for transportability and safety. The result is that the diesel engine provides the best overall performance with respect to the criteria listed in Table 17. In terms of alternative technologies the fuel cell provides the most promise at its current state of development. However, if the specific cost of the microturbine could be reduced to equal that of the other primary power sources, it would become the best choice for alternative primary power in the future.

Table 17. Primary Power Source Scoring Matrix

		Gasoline Engine (Reference)		Diesel Engine		Microturbine		Fuel Cell	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Operating Range (Specific Energy)	20%	3.05	0.61	4.80	0.96	3.33	0.67	3.00	0.60
Power/Weight Ratio (Specific Power)	10%	2.60	0.26	2.46	0.25	3.30	0.33	2.48	0.25
Efficiency (%)	20%	1.50	0.30	2.25	0.45	1.30	0.26	2.40	0.48
Power Specific Cost ($/kw)	5%	4.91	0.25	4.86	0.24	1.25	0.06	4.91	0.25
Transportability	10%	3.00	0.30	3.00	0.30	3.00	0.30	2.33	0.23
Safety	10%	3.00	0.30	3.00	0.30	2.75	0.28	2.00	0.20
Cycle Life	5%	3.22	0.16	3.22	0.16	3	0.15	3.04	0.15
	Net Score	2.18		2.66		2.04		2.16	
	Rank	2nd		1st		4th		3rd	

The scoring of the secondary power sources followed the same method as the primary power sources. The result was that the flywheel provides the best overall performance with respect to the criteria listed in Table 18.

Table 18. Secondary Power Source Scoring Matrix

		Lead Acid Battery		Ni-MH Battery		Li-Ion Battery		Flywheel		Ultracapacitor	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Operating Range (Specific Energy)	20%	0.50	0.10	0.95	0.19	1.50	0.30	1.32	0.26	0.05	0.01
Power/Weight Ratio (Specific Power)	10%	2.38	0.24	2.48	0.25	2.62	0.26	3.75	0.38	3.52	0.35
Efficiency (%)	20%	4.00	0.80	3.50	0.70	4.75	0.95	4.50	0.90	4.75	0.95
Power Specific Cost ($/kw)	1.67%	4.60	0.08	4.63	0.08	4.63	0.08	4.00	0.07	4.94	0.08
Energy Specific Cost ($/kwh)	3.33%	2.92	0.10	2.70	0.09	2.70	0.09	2.16	0.07	0.80	0.03
Transportability	10%	2.33	0.23	2.33	0.23	2.33	0.23	2.67	0.27	2.33	0.23
Safety	10%	2.00	0.20	2.00	0.20	2.00	0.20	2.75	0.28	2.00	0.20
Cycle Life	5%	2.00	0.10	2.08	0.10	2.00	0.10	5.00	0.25	5.00	0.25
	Net Score	1.85		1.84		2.21		2.47		2.10	
	Rank	4th		5th		2nd		1st		3rd	

C. SENSITIVITY ANALYSIS

To ensure the weights chosen by the user representative were not biased towards one concept, a sensitivity analysis was performed on concepts that had the highest net score for the primary and secondary power sources. Those concepts were the diesel engine and flywheel respectively. A sensitivity analysis was conducted on selection criteria that had concepts with higher weighted scores than the diesel engine or flywheel, but did not have the highest net score. To conduct the analysis, the net score was determined for the original selection criteria weight and with each chosen selection criterion weighted at a value of 1.0. These two points were then plotted for each concept and the point of intersection between dominating concepts was determined. Section V.C.1 and V.C.2 will describe the dominance and allowable variance for each of the selection criteria based on the points of intersection.

1. Sensitivity Analysis of Primary Power Source Concepts

Per Table 17, the power/weight ratio and power specific cost selection criteria have concepts with higher weighted scores than the diesel engine, but do not have the highest net score. The sensitivity of weights for these selection criteria will be examined in this section. The sensitivity of the operating range rating for the diesel engine will also be examined in this section due to it being significantly higher than the other concepts considered.

a. Power/Weight Ratio (Specific Power) Weight Sensitivity Analysis

The weighted scores of each primary power source concept at the original power/weight ratio selection criteria weight and at a value of 1.0 are shown in Table 19 and depicted in Figure 32. Trendlines were used to determine the equations of the lines representing the dominant concepts (diesel engine and microturbine). Microsoft Excel Solver was then used to solve for the point of intersection. The result was that the diesel engine was the dominant concept for power/weight ratio selection criteria weights less than 48.2 percent and the microturbine was the dominant concept for weights above 48.2 percent (see Table 20).

Table 19. Selection Criteria Weight vs. Primary Power Source Power/Weight Ratio (Specific Power) Score

Weight	Gas	Diesel	Microturbine	Fuel Cell
0.10	2.18	2.66	2.04	2.16
1.00	2.60	2.46	3.30	2.48

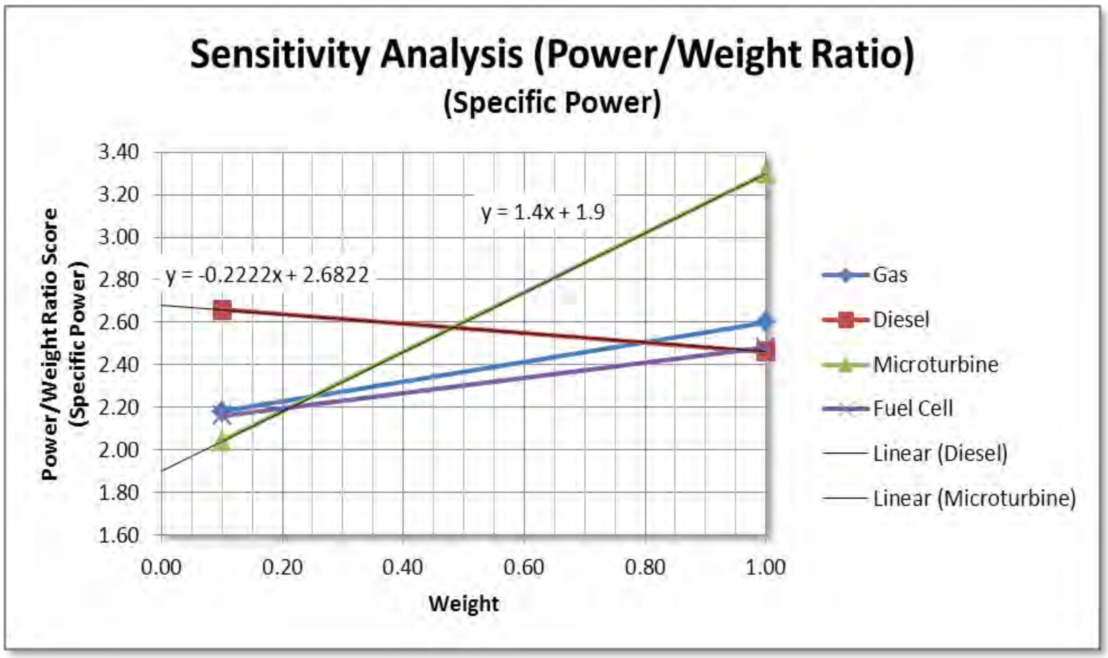

Figure 32. Sensitivity Analysis–Primary Power Source Power/Weight Ratio (Specific Power)

Table 20. Concept Point of Intersection and Dominance–Primary Power Source Power/Weight Ratio (Specific Power)

Weight	Score	Concept	Dominance
x	2.57	Microturbine	> 48.2%
48.2%	2.57	Diesel Engine	< 48.2%

b. Power Specific Cost Weight Sensitivity Analysis

The weighted scores of each primary power source concept at the original power specific cost selection criteria weight and at a value of 1.0 are shown in Table 21 and depicted in Figure 33. Trendlines were used to determine the equations of the lines

representing the dominant concepts (diesel engine and fuel cell). Microsoft Excel Solver was then used to solve for the point of intersection. The result was that the diesel engine was the dominant concept for power specific cost selection criteria weights less than 91.4 percent and the fuel cell was the dominant concept for weights above 91.4 percent (see Table 22).

Table 21. Selection Criteria Weight vs. Primary Power Source Power Specific Cost Score

Weight	Gas	Diesel	Microturbine	Fuel Cell
0.05	2.18	2.66	2.04	2.16
1.00	4.91	4.86	1.25	4.91

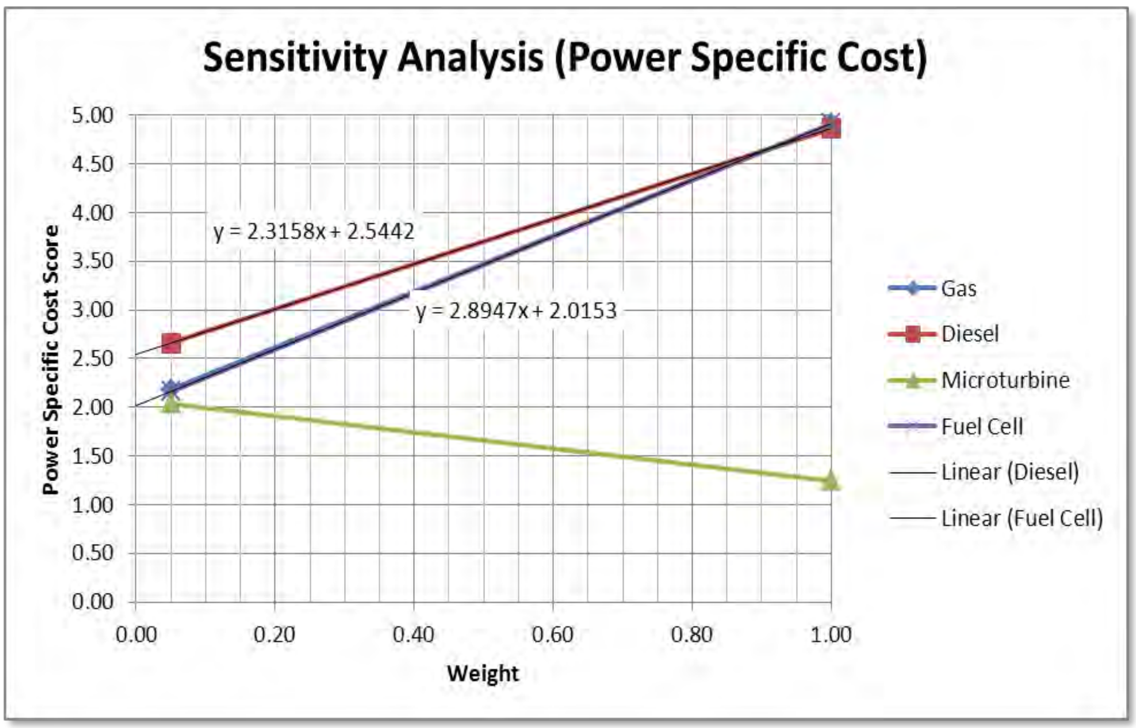

Figure 33. Sensitivity Analysis–Primary Power Source Power/Specific Cost

Table 22. Concept Point of Intersection and Dominance–Primary Power Source Power Specific Cost

Weight	Score	Concept	Dominance
x	4.66	Diesel	< 91.4%
91.4%	4.66	Fuel Cell	> 91.4%

c. Operating Range (Specific Energy) Score Sensitivity Analysis

Microsoft Excel Solver was used to determine the operating range rating which would cause the diesel engine to lose its first place ranking among the concepts considered. The result is the rating would have to decrease from 4.80 to 2.375 (see Table 23). This is equivalent to a diesel engine with a specific energy of 237 Wh/kg (per solving Equation 5-2 for specific energy).

Table 23. Operating Range Score vs. Net Score Sensitivity Analysis

		Primary Power Sources							
		Gasoline Engine (Reference)		Diesel Engine		Microturbine		Fuel Cell	
Selection Criteria	Weight	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score	Rating	Weighted Score
Operating Range (Specific Energy)	20%	3.05	0.61	**2.375**	0.47	3.33	0.67	3.00	0.60
Power/Weight Ratio (Specific Power)	10%	2.60	0.26	2.46	0.25	3.30	0.33	2.48	0.25
Efficiency (%)	20%	1.50	0.30	2.25	0.45	1.30	0.26	2.40	0.48
Power Specific Cost ($/kw)	5%	4.91	0.25	4.86	0.24	1.25	0.06	4.91	0.25
Transportability	10%	3.00	0.30	3.00	0.30	3.00	0.30	2.33	0.23
Safety	10%	3.00	0.30	3.00	0.30	2.75	0.28	2.00	0.20
Cycle Life	5%	3.22	0.16	3.22	0.16	3.00	0.15	3.04	0.15
	Net Score	2.18		**2.17**		2.04		2.16	

2. Sensitivity Analysis of Secondary Power Source Concepts

Per Table 18, the operating range and power/weight ratio selection criteria have concepts with higher weighted scores than the flywheel, but do not have the highest net score. The sensitivity of weights for these selection criteria will be examined in this section. The sensitivity of the cycle life, efficiency, and power/weight ratio ratings for the flywheel will also be examined in this section, due to the ratings being the highest or second highest among the concepts considered.

a. Operating Range (Specific Energy) Weight Sensitivity Analysis

The weighted scores of each secondary power source concept at the original operating range selection criteria weight and at a value of 1.0 are shown in Table 24 and depicted in Figure 34. Trend lines were used to determine the equations of the lines representing the dominant concepts (flywheel and Li-Ion battery). Microsoft Excel Solver was then used to solve for the point of intersection. The result was that the flywheel was the dominant concept for operating range selection criteria weights less than 67.3 percent and the Li-Ion battery was the dominant concept for weights above 67.3 percent (see Table 25).

Table 24. Selection Criteria Weight vs. Secondary Power Source Operating Range (Specific Energy) Score

Weight	Lead Acid	Ni-MH	Li-Ion	Flywheel	Ultracapacitor
0.20	1.85	1.84	2.21	2.47	2.10
1	0.50	0.95	1.50	1.32	0.05

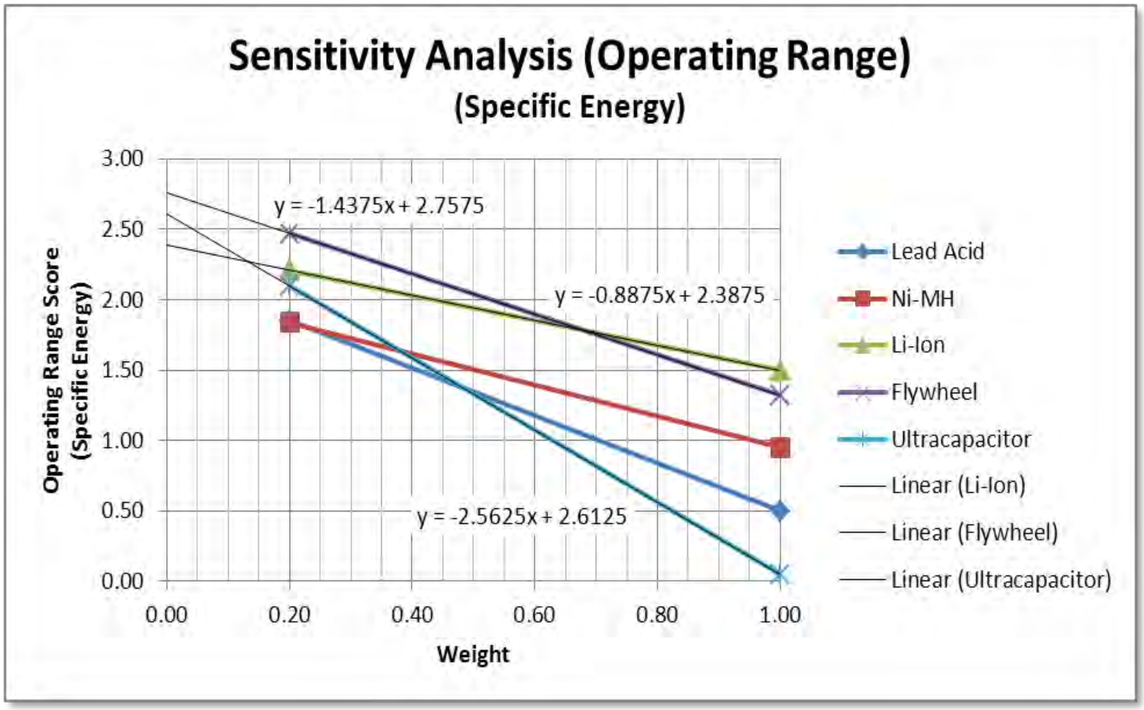

Figure 34. Sensitivity Analysis–Secondary Power Source Operating Range (Specific Energy)

Table 25. Concept Point of Intersection and Dominance–Secondary Power Source Operating Range (Specific Energy)

Weight	Score	Concept	Dominance
x	1.79	Flywheel	< 67.3%
67.3%	1.79	Li-Ion Battery	> 67.3%

b. Power/Weight Ratio (Specific Power) Weight Sensitivity Analysis

The weighted scores of each secondary power source concept at the original power/weight ratio selection criteria weight and at a value of 1.0 are shown in Table 26 and depicted in Figure 35. Trend lines were used to determine the equations of the lines representing the dominant concepts. Based on the trend lines in Figure 35, the flywheel will dominate all other secondary power source concepts studied in this paper for all operating range (specific energy) selection criteria weights.

Table 26. Selection Criteria Weight vs. Secondary Power Source Power/Weight Ratio (Specific Power) Score

Weight	Lead Acid	Ni-MH	Li-Ion	Flywheel	Ultracapacitor
0.10	1.85	1.84	2.21	2.47	2.10
1	2.38	2.48	2.62	3.75	3.52

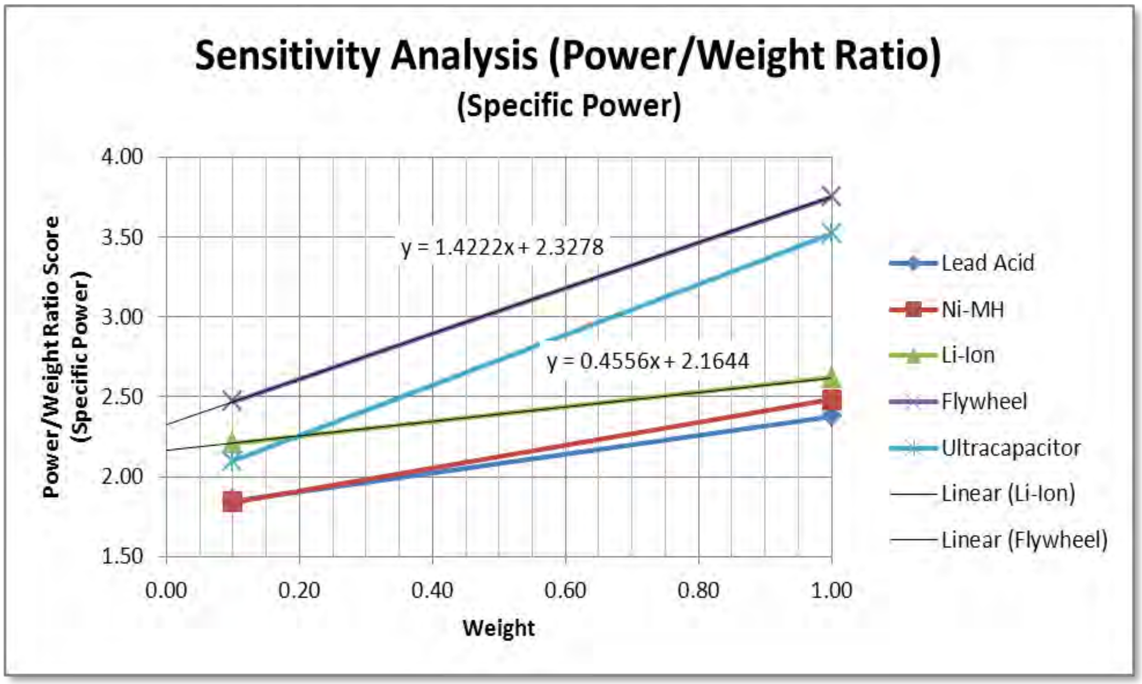

Figure 35. Sensitivity Analysis–Secondary Power Source Power/Weight Ratio (Specific Power)

c. *Cycle Life Score Sensitivity Analysis*

Microsoft Excel Solver was used to determine the cycle life rating which would cause the flywheel to lose its first place ranking among the concepts considered. The result is the rating would have to decrease from 5.00 to zero (see Table 27). This is equivalent to a flywheel with a cycle life of 10 cycles (per solving Equation 5-4 for cycle life).

Table 27. Cycle Life Score Sensitivity Analysis

		Secondary Power Source									
		Lead Acid Battery		Ni-MH Battery		Li-Ion Battery		Flywheel		Ultracapacitor	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Operating Range (Specific Energy)	20%	0.50	0.10	0.95	0.19	1.50	0.30	1.32	0.26	0.05	0.01
Power/Weight Ratio (Specific Power)	10%	2.38	0.24	2.48	0.25	2.62	0.26	3.75	0.38	3.52	0.35
Efficiency (%)	20%	4.00	0.80	3.50	0.70	4.75	0.95	4.50	0.90	4.75	0.95
Power Specific Cost ($/kw)	1.67%	4.60	0.08	4.63	0.08	4.63	0.08	4.00	0.07	4.94	0.08
Energy Specific Cost ($/kwh)	3.33%	2.92	0.10	2.70	0.09	2.70	0.09	2.16	0.07	0.80	0.03
Transportability	10%	2.33	0.23	2.33	0.23	2.33	0.23	2.67	0.27	2.33	0.23
Safety	10%	2.00	0.20	2.00	0.20	2.00	0.20	2.75	0.28	2.00	0.20
Cycle Life	5%	2.00	0.10	2.08	0.10	2.00	0.10	0.00	0.00	5.00	0.25
Net Score		1.85		1.84		2.21		2.22		2.10	

d. Efficiency Score Sensitivity Analysis

Microsoft Excel Solver was used to determine the efficiency rating which would cause the flywheel to lose its first place ranking among the concepts considered. The result is the rating would have to decrease from 4.50 to 3.18 (see Table 28). This is equivalent to a flywheel with an efficiency of 63.56 percent (per solving Equation 5-3 for efficiency).

Table 28. Efficiency Score Sensitivity Analysis

		Secondary Power Source									
		Lead Acid Battery		Ni-MH Battery		Li-Ion Battery		Flywheel		Ultracapacitor	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Operating Range (Specific Energy)	20%	0.50	0.10	0.95	0.19	1.50	0.30	1.32	0.26	0.05	0.01
Power/Weight Ratio (Specific Power)	10%	2.38	0.24	2.48	0.25	2.62	0.26	3.75	0.38	3.52	0.35
Efficiency (%)	20%	4.00	0.80	3.50	0.70	4.75	0.95	3.18	0.64	4.75	0.95
Power Specific Cost ($/kw)	1.67%	4.60	0.08	4.63	0.08	4.63	0.08	4.00	0.07	4.94	0.08
Energy Specific Cost ($/kwh)	3.33%	2.92	0.10	2.70	0.09	2.70	0.09	2.16	0.07	0.80	0.03
Transportability	10%	2.33	0.23	2.33	0.23	2.33	0.23	2.67	0.27	2.33	0.23
Safety	10%	2.00	0.20	2.00	0.20	2.00	0.20	2.75	0.28	2.00	0.20
Cycle Life	5%	2.00	0.10	2.08	0.10	2.00	0.10	5.00	0.25	5.00	0.25
	Net Score	1.85		1.84		2.21		2.20		2.10	

e. Power/Weight Ratio (Specific Power) Score Sensitivity Analysis

Microsoft Excel Solver was used to determine the power/weight ratio (specific power) rating which would cause the flywheel to lose its first place ranking among the concepts considered. The result is the rating would have to decrease from 3.75 to 1.11 (see Table 29). This is equivalent to a flywheel with a specific power of 12.75 W/kg (per solving Equation 5-1 for specific power).

Table 29. Power/Weight Ratio Score Sensitivity Analysis

		Secondary Power Source									
		Lead Acid Battery		**Ni-MH Battery**		**Li-Ion Battery**		**Flywheel**		**Ultracapacitor**	
Selection Criteria	**Weight**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**	**Rating**	**Weighted Score**
Operating Range (Specific Energy)	20%	0.50	0.10	0.95	0.19	1.50	0.30	1.32	0.26	0.05	0.01
Power/Weight Ratio (Specific Power)	10%	2.38	0.24	2.48	0.25	2.62	0.26	1.11	0.11	3.52	0.35
Efficiency (%)	20%	4.00	0.80	3.50	0.70	4.75	0.95	4.50	0.90	4.75	0.95
Power Specific Cost ($/kw)	1.67%	4.60	0.08	4.63	0.08	4.63	0.08	4.00	0.07	4.94	0.08
Energy Specific Cost ($/kwh)	3.33%	2.92	0.10	2.70	0.09	2.70	0.09	2.16	0.07	0.80	0.03
Transportability	10%	2.33	0.23	2.33	0.23	2.33	0.23	2.67	0.27	2.33	0.23
Safety	10%	2.00	0.20	2.00	0.20	2.00	0.20	2.75	0.28	2.00	0.20
Cycle Life	5%	2.00	0.10	2.08	0.10	2.00	0.10	5.00	0.25	5.00	0.25
Net Score		1.85		1.84		2.21		2.20		2.10	

D. HYBRID DRIVETRAIN ARCHITECTURE RECOMMENDATION

The choice of a drivetrain for a tactical vehicle must be one that considers all aspects of performance and types of use. The integration of a hybrid drivetrain must provide improved capabilities in the areas of performance and/or efficiency. This paper analyzed each of the available hybrid technologies in terms of quantitative and qualitative selection criteria. The complexity of a vehicle drivetrain and the manner in which the selection criteria were influenced by the drivetrain architecture drove the choice to use of the additive weighting method of evaluation for multiple criteria. By taking the average of the net scores for the best performing primary and secondary power sources and adding the net score for the best performing general hybrid architecture resulted in an aggregate net score of 3.25 ((2.66 + 2.47)/2 + 0.68 = 3.25) for a series hybrid with a diesel engine primary power source and a flywheel secondary power source. To further describe the architecture, it is recommended that permanent magnet motors are used for the traction motor(s) within the drivetrain (per Table 16).

E. RECOMMENDED HYBRID DRIVETRAIN ARCHITECTURE OPERATIONAL EFFECTIVENESS

In an operational environment commanders are primarily interested in the capabilities that a tactical vehicle provides in completing missions. To this end operational commanders are interested in reducing fuel consumption to enable forces to be more agile while maintaining performance against mobility, transportability, survivability, and safety. The use of a series hybrid with a diesel engine primary power source and a flywheel secondary power source provides many enhanced capabilities over that of a conventional drivetrain vehicle. The recommended architecture provides improved operating range, power to weight ratios, energy efficiency, export power, and the additional capability of silent movement. The recommended hybrid drivetrain architecture also provides improvements in all areas of mobility and survivability with the exception of braking and magnetic signatures respectively. The transportability and safety capabilities are mildly degraded due to additional special training and handling procedures required to handle the stored energy in the flywheel in the areas of air

transportation and general maintenance and repair. From a system perspective, the recommended hybrid drivetrain architecture is operationally effective, provides improved and new capabilities, with few and easily mitigated degradations in capability.

F. CHAPTER SUMMARY

The decision evaluation theory applied in this chapter consisted of the additive weighting method for multiple criteria. The additive weighting method provided the capability for the strength of a design concept in one selection criteria to compensate for a weakness in another. The weights given to each selection criteria allowed the user representatives to place higher importance on specific criteria related to improving mission success. The end result was a well-balanced design concept that provided improved performance in many areas and offered additional capability not available with a conventional drivetrain. The sensitivity analysis conducted on the selection criteria weights and rankings showed that the recommended drivetrain architecture was a robust choice. The weights of analyzed selection criteria would have to change by more than 35 percent and rankings would have to change by more than 30 percent for the recommend architecture to change.

VI. CONCLUSIONS

A. KEY POINTS AND RECOMMENDATIONS

Operational agility and risk reduction have become the driving force behind an increased emphasis by operational commanders and military leaders on reducing fuel consumption in tactical vehicles. The rising use of irregular warfare has levied higher threat risks to support convoys. The ability to reduce the size of support operations while simultaneously increasing operational range is a great tactical benefit to the military's ground vehicle fleet. The fuel economy of a vehicle is dependent on complex interactions of vehicle characteristics and component efficiencies. This paper focused on the selection of a hybrid drivetrain architecture that reduces fuel consumption while maintaining performance against mobility, transportability, survivability, and safety requirements.

In the evaluation of hybrid drivetrain architectures for tactical vehicles it is important to incorporate consideration of the duty cycle. Methods of employment of a vehicle can influence the importance given to each of the selection criteria by user representatives. Once the Tank and Automotive Research, Development and Engineering Center (TARDEC) makes the duty cycle experiments (DCEs) for convoy escort (DCE 4) and urban assault (DCE 5) missions (see Figure 36) publicly available it is recommended that the fuel economy of the HMMWV and the fully burdened cost of fuel be recalculated to provide more accurate numbers of what a tactical vehicle will experience in operation (Pozolo, 2009). By using the TARDEC developed DCEs instead of the duty cycles used by the EPA (city and highway), it will provide a more accurate picture of which type of hybrid architectures provide the most benefit for the mix of missions that the vehicle will conduct.

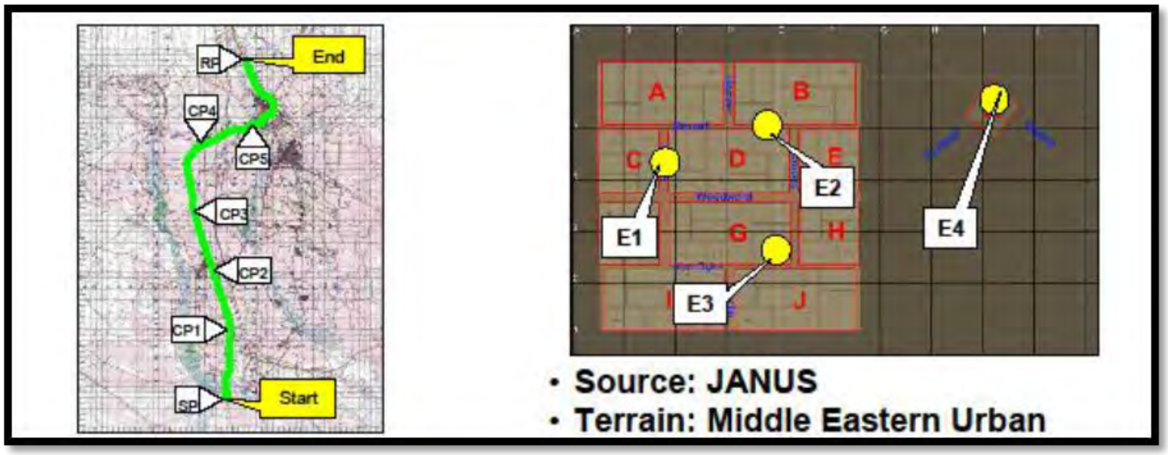

Figure 36. Convoy Escort & Urban Assault Mission Examples. (From Pozolo, 2009)

The rating of the selection criteria for hybrid drivetrains is not always a direct comparison of component performance parameters. The mobility and survivability capabilities were dependent on the general hybrid architecture and the transportability and safety capabilities were dependent on the form of energy storage. Therefore, it is important to consider the dependencies of the selection criteria when developing the algorithm for the concept selection net score.

Multiple criterion decision theory and the relative importance of the selection criteria provided by the user representative suggest that a series hybrid drivetrain utilizing a diesel primary power source and a flywheel secondary power source provides the best balance among the alternatives. The tradeoff surveys in Appendix A support the selection of a series hybrid drivetrain architecture. When the respondents were asked questions to determine their willingness to incur a weight penalty or increased logistical footprint based on performance parameters, their responses often indicated that the weight penalty of a series hybrid was their threshold for the tradeoff.

B. AREAS TO CONDUCT FURTHER RESEARCH

Continued research related to the selection of hybrid drivetrain architectures should include monitoring new and developing technologies and capabilities. Hydraulic hybrids was a technology that was not explicitly evaluated in this paper and should be

considered as an option for a hybrid drivetrain architecture as more research and data becomes available. Export power available from many hybrid drivetrain concepts leaves the door open for future pulse power weapons and armor concepts to be powered by a tactical vehicle. Improvements in lethality and survivability can be gained through the introduction of electro-magnetic guns, lasers, microwave weapons and electro-magnetic active armor. Additionally, as technologies evaluated in this paper become more mature, the concepts should re-evaluated as concept capabilities increase and specific costs decrease over time.

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APPENDIX A–SURVEYS

Tactical Ground Vehicle–Attribute Weighting Survey

Naval Post Graduate School
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Please complete the following survey from the perspective of providing the relative importance of the vehicle attributes listed based on the customer's (warfighter's) perspective. Please complete this survey and return it to me via email at your convenience. Thank you!

Organization	HQMC, CD&I, FMID, Booz Allen Hamilton
Position Title	Systems Engineer for capability development
Name	Mark Pflanz
Work E-mail	Mark.pflanz.ctr@usmc.mil
Work Phone	703-784-0605
Work Address	3300 Russell Road, Quantico, VA

Vehicle Attribute	**Relative Importance (out of 100%)**
Operating Range	20%
Power to Weight Ratio	10%
Efficiency	20%
Cost	5%
Logistical Footprint/Complexity (i.e. # of components)	5%
Mobility	10%
Transportability	10%
Safety	10%
Survivability	5%

Cycle Life	5%

Additional comments:
Hi mark, here's what I'd put: I'd bin them into three categories: marked as 20, 10, 5. Overall, there is such a strong push on efficiency and taking fuelers off the road, efficiency is key. Range is also key (20's). Followed by mobility, transportability, and safety (equal), these are the 10's. Followed by what's left. Rather than acceleration, recommend maybe consider power to weight ratio, which is close to acceleration, but not equivalent. Hope this helps. Good luck, mark.

Hybrid vs. Conventional Drivetrains–Tradeoff Survey

Naval Post Graduate School
Masters in Systems Engineering Management Thesis
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Please complete the following survey from the perspective of comparing the current capabilities of the HMMWV and the "User's" willingness to make tradeoffs for gains in fuel economy. Please complete this survey and return it to me via email at your convenience. Thank you!

Organization	HQMC, CD&I, FMID, Booz Allen Hamilton
Position Title	Systems Engineer for capability development
Name	Mark Pflanz
Work E-mail	Mark.pflanz.ctr@usmc.mil
Work Phone	703-784-0605
Work Address	3300 Russell Road, Quantico, VA

Statement	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Fuel Economy					
I would trade an increase in vehicle weight of 150 lbs for a 50% increase in fuel economy in stop and go driving conditions.	x				
I would trade an increase in vehicle weight of 500 lbs for a 50% increase in fuel economy in stop and go driving conditions.	x				
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50%		x			

increase in fuel economy in stop and go driving conditions.					
I would trade an increase in vehicle weight of 150 lbs for a 50% increase in fuel economy in constant speed driving conditions.	x				
I would trade an increase in vehicle weight of 500 lbs for a 50% increase in fuel economy in constant speed driving conditions.	x				
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50% increase in fuel economy in constant speed conditions.	x				
Operating Range					
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 20% increase in operating range	x				
I would trade an increase in vehicle weight of 150 lbs for a 20% increase in operating range	x				
I would trade an increase in vehicle weight of 500 lbs for a 20% increase in operating range	x				
Top Speed					
I would trade an increase in vehicle weight of 150 lbs for a 20% increase in top speed				x	
I would trade an increase in vehicle weight of 500 lbs for a 20% increase in top speed				x	
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 20% increase in top speed				x	
Acceleration Time					
I would trade an increase in vehicle weight of 150 lbs for a 50% reduction in 0-60mph acceleration time		x			
I would trade an increase in vehicle weight of 500 lbs for a 50% reduction in 0-60mph acceleration time			x		

I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50% reduction in 0-60mph acceleration time				x	
Portable Power Generation					
I would trade an increase in vehicle weight of 150 lbs for portable power generation capable of powering a mobile command post or a field hospital	x				
I would trade an increase in vehicle weight of 500 lbs for portable power generation capable of powering a mobile command post or a field hospital			x		
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for portable power generation capable of powering a mobile command post or a field hospital				x	

Additional comments:
Hi mark, JLTV is going thru some interesting on-board / off board power analysis, as well as fuel economy. Interestingly, the new ISG/IPG technologies are providing large payoffs in terms of efficiency. We are also lucky to have some of the Army's HEVEA program (Hybrid electric test program) on the JTLV PM team in Selfridge, MI. One of them is John Putrus, whom I'd recommend contacting; he's probably one of the smartest people I know on this topic. (Johnathon.Putrus@us.army.mil) He led the HEVEA program at one point, and found some interesting test results in reference to the military drive cycle (duty profile) and HE tech. Partly, their testing showed that the military duty cycle couldn't really take significant advantage of HE because the military duty cycle didn't involve enough stop and go, although hill type traffic did help. Check with John, he can fill you in. There was an HE advantage, but not a huge one. On a separate topic, The JLTV AoA results are showing some large gains in fuel efficiency and power generation based on an ISG combination. The ONR results show a potential of perhaps 10-20% at most with HE technology. Long story short, is that since we spend so much time idling to power on board systems, the efficiency gains over the long term of an ISG are very close to that which might be experienced by a HE system: each shows a potential of 10-20% gains in overall fuel use. I'd guess each is lower, but even a 10% gain is I suppose a big deal perhaps. Moreover, the ISG combination lays a ground work for any future HE integration. Something to consider in terms of incremental transitions, since both technologies move in similar directions. (my assessment of two different lines of analysis, not a documented analysis result in and of itself). Hope this helps, glad to talk more at your convenience, call me in FMID anytime. Take care, mark

Organization	PM JLTV

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Statement	**Strongly Agree**	**Agree**	**Neutral**	**Disagree**	**Strongly Disagree**
Fuel Economy					
I would trade an increase in vehicle weight of 150 lbs for a 50% increase in fuel economy in stop and go driving conditions.	X				
I would trade an increase in vehicle weight of 500 lbs for a 50% increase in fuel economy in stop and go driving conditions.	X				
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50% increase in fuel economy in stop and go driving conditions.	X				
I would trade an increase in vehicle weight of 150 lbs for a 50% increase in fuel economy in constant speed driving conditions.	X				
I would trade an increase in vehicle weight of 500 lbs for a 50% increase in fuel economy in constant speed driving conditions.	X				
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50% increase in fuel economy in constant speed conditions.	X				
Operating Range					
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 20% increase in operating range		X			

I would trade an increase in vehicle weight of 150 lbs for a 20% increase in operating range		X			
I would trade an increase in vehicle weight of 500 lbs for a 20% increase in operating range		X			
Top Speed					
I would trade an increase in vehicle weight of 150 lbs for a 20% increase in top speed		X			
I would trade an increase in vehicle weight of 500 lbs for a 20% increase in top speed				X	
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 20% increase in top speed				X	
Acceleration Time					
I would trade an increase in vehicle weight of 150 lbs for a 50% reduction in 0-60mph acceleration time	X				
I would trade an increase in vehicle weight of 500 lbs for a 50% reduction in 0-60mph acceleration time				X	
I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for a 50% reduction in 0-60mph acceleration time				X	
Portable Power Generation					
I would trade an increase in vehicle weight of 150 lbs for portable power generation capable of powering a mobile command post or a field hospital	X				
I would trade an increase in vehicle weight of 500 lbs for portable power generation capable of powering a mobile command post or a field hospital			X		

<table>
<tr><td>I would trade an increase in the logistical footprint of a vehicle due to an increased number of drivetrain components for portable power generation capable of powering a mobile command post or a field hospital</td><td></td><td>X</td><td></td><td></td><td></td></tr>
<tr><td colspan="6">Additional comments:
I would just note that some of the questions and scenarios would not be possible for the amount of weight or just by switching to a hybrid system.</td></tr>
</table>

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APPENDIX B–CALCULATION OF HMMWV FUEL ECONOMY

In the absence of an operational mission duty cycle, the Environmental Protection Agency's (EPA) Urban Dynamometer Driving Schedule (UDDS) and Highway Fuel Economy Driving Schedule (HWFET) standard cycles were used together with the HMMWV characteristics from Table 30 to calculate a fuel economy of 9.2 mpg city and 13.4 mpg highway for a HMMWV. This equates to an average fuel economy of 11.3 mpg for a HMMWV. The UDDS represents city driving, while the HWFET duty cycle represents highway driving conditions under 60 mph. Assuming the same brake specific fuel consumption (0.555 lb/hp-hr), the HWWMV will consume 0.62 gallons of fuel per hour during idling (Frame & Blanks, 2004).

Table 30. HMMWV M1097 A2 specifications.
(After 21st Century Truck Program, 2000)

Attribute	**Value**
Configuration	4x4 cargo/shelter/troop carrier
Engine manufacturer	GM IDI Diesel
Aspiration	Natural
Engine displacement (L)	6.5
Engine peak power (kW)	119 @3,400 rpm
Transmission	GMPT automatic
Empty vehicle weight (curb) (kg)	2,676
Gross vehicle weight (kg)	4,672
Frontal area (m2)	3.58
Coefficient of drag	0.5
Wheel base (m)	3.3
Tire type	Goodyear radial 37
Rolling radius (m)	0.4558
Coefficient of rolling resistance	0.013 paved/0.045 off road
Acceleration 0–30 mph (second)	10
Acceleration 0–50 mph (second)	29

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